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THESIS

AN ANALYSIS OF THE FEASIBILITY OF IMPLEMENTING ULTRA WIDEBAND AND MESH NETWORK TECHNOLOGY IN SUPPORT OF MILITARY OPERATIONS

by

Joseph F. Herzig Jr.

March 2005

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This thesis analyzes the feasibility, functionality, and usability of Ultra Wideband technology as an alternative to 802.11 in wireless mesh networks for multiple DoD contexts. Ultra wideband and wireless mesh network technologies and applications are researched and analyzed through multiple field and lab experiments for usability in current, real-world situations. Hardware and software investigations are conducted to determine any implementation issues between ultra wideband and wireless mesh networks. A detailed assessment is conducted of the various elements and operational constraints for developing an ultra wideband mesh network that can be utilized to improve situational awareness in network-centric operations. Through joint research with Lawrence Livermore National Laboratories, various hardware and software components are developed to create a test bed for tactical level ultra wideband and mesh networking experimentation in a highly mobile environment. This thesis also lays the groundwork into future ultra wideband and mesh networking applications.

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ACRONYMS AND ABBREVIATIONS

AODV	Ad-Hoc On-Demand Distance Vector
AP	Access Point
BPS	Breaths Per Second
C3I	Command, Control, Communications, and Intelligence
COTS	Commercial Off-The-Shelf
DoD	Department of Defense
DSR	Dynamic Source Routing
ETX	Expected Transmission Count
FCC	Federal Communications Commission
GIG	Global Information Grid
GIGA	Global Information Grid Applications
GPR	Ground Penetration Radar
HMMWV	High-Mobility Multi-Purpose Wheeled Vehicle
IBSS	Independent Basic Service Area
IEEE	Institute of Electrical and Electronics Engineers
LAN	Local Area Network
LANMAR	Landmark Ad-Hoc Routing
LLNL	Lawrence Livermore National Laboratories
LPD	Low Probability of Detection
LPI	Low Probability of Intercept
LQ	Link Quality
MID	Multiple Interface Declaration
MMRP	Mobile Mesh Routing Protocol
MPR	Multipoint Relay
NIC	Network Interface Card
NLQ	Neighbor Link Quality
NOC	Network Operations Center
NPS	Naval Postgraduate School
OLSR	Optimized Link State Routing

OSI	Open System Interconnection
PCMCIA	Personal Computer Memory Card International Association
PRF	Pulse Repetition Frequency
RADAR	Radio Direction and Ranging
RAM	Random Access Memory
RF	Radio Frequency
RFC	Request for Comments
SA	Situational Awareness
SDRAM	Synchronous Dynamic Random Access Memory
SNMP	Simple Network Management Protocol
SOCOM	Special Operations Command
TACSAT	Tactical Satellite
TBPRF	Topology Dissemination Based on Reverse-Path Forwarding
TC	Topology Control
TNT	Tactical Network Topology
TOC	Tactical Operations Center
UAV	Unmanned Aerial Vehicle
USB	Universal Serial Bus
UWB	Ultra Wideband
ZRP	Zone Routing Protocol

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To my wonderful family, thank you Brad and Anne-Marie for being well behaved and supportive during my studies here at NPS. Finally, my beautiful wife Kim, thank you for being supportive, understanding and for making the huge sacrifices necessary both here and throughout my naval career. I look forward to our future happiness and enjoyment as a family.

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I. INTRODUCTION

A. BACKGROUND

Wireless networking has developed into a very popular networking architecture solution for many various situations and environments. The use of a traditional point-to-point or point-to-multipoint wireless network is constrained by the requirement to have access points (AP) at assorted locations to provide a link to a wired network. The link to a wired network provides a means of communicating over an extended distance to a larger network or the global internet. The use of access points poses a problem because it limits the amount of distance between individual nodes to the radio range of the wireless medium used. A multipoint-to-multipoint architecture, in which every node in the network becomes a router, is an effective means of attaining larger coverage distances with less investment in infrastructure.

True wireless ad hoc mesh networks are self-organizing, self-healing, self-balancing, and self-aware. The central scheme that enables mesh networking is the idea of dynamic, node-based routing. Self-organizing networks form when every node has the capability to join and create a network automatically upon discovering neighboring nodes with similar characteristics and capabilities within radio range. Each node will have network self-awareness of its surrounding environment and will be able to make efficient informed routing decisions continuously while operating. If a node in the routing table is lost or degraded, another route or path is chosen automatically. The more nodes that are added, the stronger and more robust the mesh network will become. The addition of every new node helps balance and share the network load; this creates a sense of self-balancing in the network. Load balancing and route control functions are shifted from dedicated network routers to the routing nodes of the mesh.[1]

Traditionally mesh networks have concentrated on the commercial off the shelf (COTS) Institute of Electronic and Electrical Engineers (IEEE) 802.X standard as the physical medium of choice between mesh network nodes. Ultra wideband (UWB) offers

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[1] Bach, E.J. and Fickel, M.G., *An Analysis of the Feasibility and Applicability of IEEE 802.X Wireless Mesh Networks Within the Global Information Grid,* Master's Thesis, Naval Postgraduate School, Monterey, California, September 2004, 1.

an alternate physical layer medium between mesh nodes. Ultra wideband provides several key advantages over IEEE 802.X:

- Low power requirements
- High bandwidth
- Extended ranges
- Low probability of intercept
- Low probability of detection
- Ability to penetrate structures that 802.X is not capable of
- Precision location

The inherent characteristics of ultra wideband make it a formidable alternate link between network nodes.

Once the underlying substrate of the wireless mesh is established, application layer possibilities begin to emerge that may have great implications for the Global Information Grid (GIG) and the Department of Defense (DoD) systems of the future.[2]

B. OBJECTIVES

This thesis intends to lay the groundwork for future study of mobile ad hoc and wireless ultra wideband mesh networking topics related to the Department of Defense's Global Information Grid environment. The GIG is the, "globally interconnected, end-to-end set of information capabilities, associated processes, and personnel for collecting, processing, storing, disseminating and managing information on demand to warfighters, policymakers, and support personnel."[3]

The objective of this research is to outline current challenges of creating an ever-present, ultra wideband mesh network across the GIG; as well as too investigate possible steps to take to move toward that lofty goal.

An evaluation and joint research with Lawrence Livermore National Laboratories (LLNL) of the current mesh networking, ultra wideband hardware and software in order to create an initial topology of available technology is integral to future work in this area.

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[2] Bach, E.J. and Fickel, M.G., *An Analysis of the Feasibility and Applicability of IEEE 802.X Wireless Mesh Networks Within the Global Information Grid,* Master's Thesis, Naval Postgraduate School, Monterey, California, September 2004, 1.

[3] Department of Defense Directive 8100.1. "Global Information Grid Overarching Policy." Dated 19 September 2002, 8.

There are two benefits of this research. First, by conducting a detailed examination of new technology and applications that may be usable in critical operating environments in which traditional wired and wireless network deployment is infeasible or not cost effective, we have attempted to begin the work of deploying a collection of components to build the ultra wideband mesh segments of the Global Information Grid. Second, by creating a test bed for follow-on research, I have established physical and logical tools to allow for a more in-depth study of ultra wideband mesh technologies by future Naval Postgraduate School (NPS) students.

C. RESEARCH QUESTIONS

My primary research question explores what the variable elements, operational constraints, and possible decision points are for developing a usable, robust, self-organizing, wireless mesh network that can be leveraged for maximum usability and shared situational awareness in network-centric operations. Additionally, I teamed up with LLNL to experiment with ultra wideband technology, as a viable physical layer solution, for adaptation into a tactical mesh network. Based on these experiments, I examined the composition and behavioral characteristics of a usable, deployable prototypical mesh testbed. Finally, I attempted to draw a conclusion about the feasibility of utilizing ultra wideband technology as a physical layer alterative in a mesh network and what the operational impact will mean to users of the GIG.

D. SCOPE

The scope of the thesis is wide to enable follow-on research. It covers the analysis of issues involved in applying ultra wideband technology into a wireless mesh networking solution. Wireless security issues have been omitted at the middle to upper Open System Interconnection (OSI) layers but discussed in detail at the physical layer due to the inherent characteristics of ultra wideband technology. Multiple field and laboratory experiments using currently available, commercial-off-the-shelf technologies and LLNL prototype ultra wideband equipment form the decision points that can be utilized for future architecture and application development, and research areas.

E. METHODOLOGY

My methodology included extensive research of the available literature, both hard copy and electronic, as well as any shared experiences with Lawrence Livermore

National Laboratories on mesh networking and ultra wideband technology theory. I examined the available literature to try to gain knowledge on as many facets of wireless mesh networks and ultra wideband technology as I could. The primary source of knowledge gathered occurred during my participation in the Naval Postgraduate School's Tactical Network Topology (TNT) series of experiments and my hands-on testing with LLNL.

I collected data by capturing relevant network performance metrics, direct routing information contained within the mesh nodes themselves, as well as general observations.

F. ORGANIZATION OF THE THESIS

The organization of the thesis is as follows:

Chapter II provides an overview of mesh networks and simple ad hoc networks and their characteristics and differences. Routing protocols will covered that are currently under active development or that hold promise from a military point of view. My focus will be on pro-active table driven routing protocols specifically Optimized Link State Routing (OLSR) rather than a reactive style routing protocol. In addition, I will briefly touch on basic mesh infrastructure types and how they can be mixed and fused with other communications technologies.

Chapter III briefly explains ultra wideband technology and its potential as an OSI layer one alternative. The inherent characteristics and capabilities of ultra wideband technology are discussed and how it pertains in a military setting. Additionally, I will describe the currently available UWB applications It will also address any problems that will be foreseen during the upcoming field experiments.

Chapter IV addresses the detailed findings and the results of the Tactical Network Topology field experiments and any problems that were encountered that significantly affected our testing.

Chapter V will provide several ultra wideband military applications that can be integrated within the Department of Defense. In addition, any standalone systems that have potential military relevance will also be explained.

Chapter VI contains my conclusions on the feasibility and applicability of using ultra wideband technology as an OSI layer one alternative to IEEE 802.X in a wireless mesh network. I will also include any future research possibilities and any possible future enhancements to be investigated in the area of ultra wideband and wireless mesh networks.

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II. WIRELESS MESH

A. WIRELESS MESH EXPLAINED

A mesh network is a highly capable form of independent basic service set (IBSS) or ad-hoc network. Nodes communicate directly to one another in an ad-hoc network. If a node desires to communicate within an ad-hoc network, that node must remain in direct communication or wireless range with all nodes they desire to pass data to. This dilemma equates to limited mobility for nodes in an ad-hoc network. The following figure is an example of an ad-hoc network.

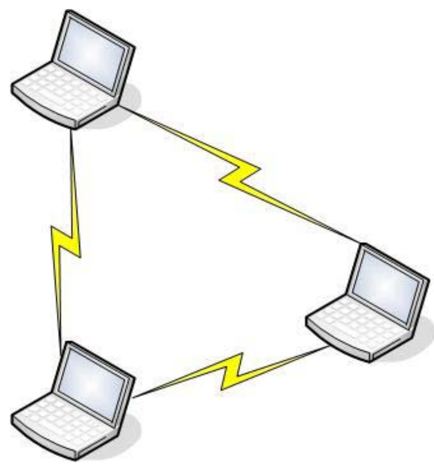

Figure 1. Ad-Hoc Network

In a wireless mesh network, every node can send and receive messages, function as a router, and relay messages for its neighbors. This relaying process enables every node to provide a multi-hop routing function. This offers a solution to the mobility dilemma that exists in an ad-hoc network. A packet of wireless data can find its way to its destination by passing through any number of intermediate nodes that contain a reliable communications link. Figure 2 provides an illustration of a wireless mesh network.

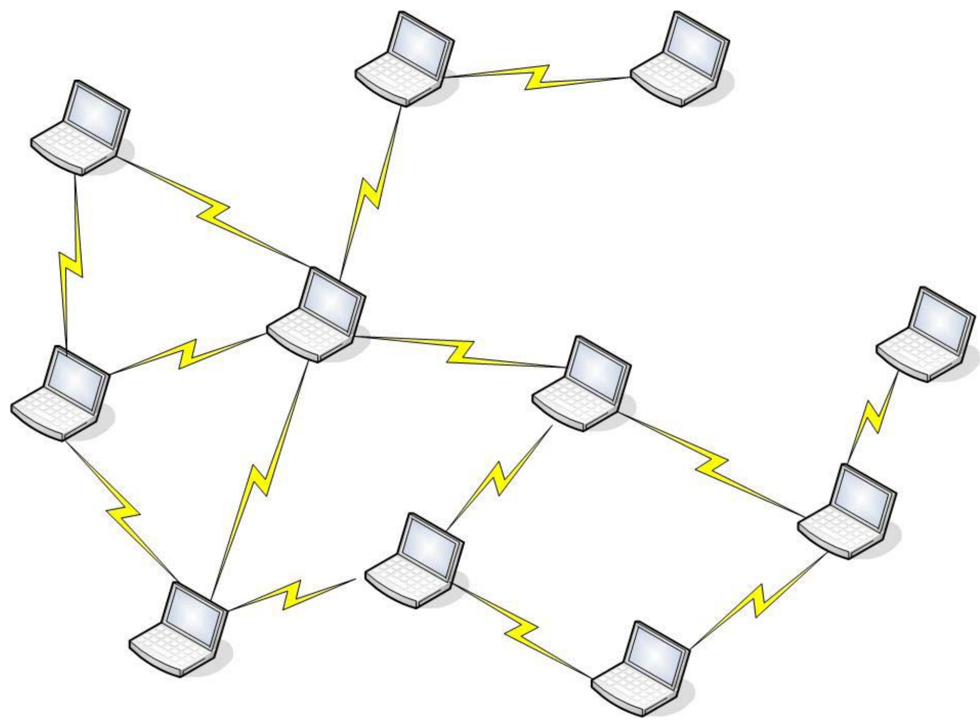

Figure 2. Mesh Network

B. DESIRABLE CHARACTERISTICS OF WIRELESS MESH NETWORKS

In order to consider wireless mesh networks a viable heir to traditional wired and wireless networks, it must provide some attractive capabilities. Several characteristics of mesh networking are attractive.

Mesh networks are self-forming. Due to the inherent routing algorithms of a mesh network, neighboring nodes discover each other either on-demand or continuously. Once a similar wireless device comes into communications range of another node, the routing tables of its neighbors automatically add that member when the situation warrants it.

Mesh technology extends a wireless network. Nodes are no longer fixed to a specific access point or network node by its own radio range. Because a mesh node can provide multi-hop routing capability, imagine a chain of mesh nodes developing that can extend the wireless network out great distances. As more nodes are added, the physical reach and strength of the network grows accordingly.

Another characteristic of wireless mesh networks that make them attractive as a networking paradigm is the same element that makes the Internet viable. The ability to do peer-to-peer routing, as is the case within the backbone of the Internet, adds redundancy to the vital communication links from end-to-end. This added redundancy brings reliability and availability gains that, in a wireless network, are essential to effective operation at the edges.[4] This redundancy and the ability to self-form provide a sense of self-healing. As nodes become disabled, routing tables update presenting an alternate means of bridging gaps that might have created a break in a communications link.

C. ROUTING ALGORITHM AND PROTOCOL OVERVIEW

In a wireless mesh network, computers are placed in an ad-hoc operating mode with any of several styles of protocols loaded and utilized to accomplish the layer 3, multi-hop routing that establishes mesh characteristics. These protocols fall into three categories, active, passive and hybrids.

1. Proactive Protocols

Proactive protocol behavior stem from every node in a network attempting to maintain routes to its existing destinations that are within radio range at all times. This behavior is necessary to maintain routing tables in the event of a data transfer either from them or as an intermediate node relaying data.

The use of proactive protocols offers the greatest flexibility and robustness necessary in a military environment. High-speed mobility in a military setting necessitates a continuously updated routing table for data forwarding. Several proactive protocols are currently available, Optimized Link State Routing (OLSR), Mobile Mesh Routing Protocol (MMRP), and Topology dissemination Based on Reverse-Path Forwarding (TBPRF) to name a few. My thesis focused on OLSR as the proactive protocol of choice for my experiments and incorporation into the Naval Postgraduate School's Tactical Network Topology (TNT).

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[4] Bach, E.J. and Fickel, M.G., *An Analysis of the Feasibility and Applicability of IEEE 802.X Wireless Mesh Networks Within the Global Information Grid,* Master's Thesis, Naval Postgraduate School, Monterey, California, September 2004, 6.

The OLSR protocol is an optimization of the classical link state algorithm tailored to the requirements of a mobile wireless LAN. In a classical link state algorithm, all link state information is flooded throughout the network. The key concept used in the protocol is that of multipoint relays (MPRs). MPRs are selected nodes that forward broadcast messages during the flooding process. This technique substantially reduces the message overhead as compared to a classical flooding mechanism, where every node retransmits each message when it receives the first copy of the message. In OLSR, only nodes elected as MPRs generate link state information. Thus, a second optimization is achieved by minimizing the number of control messages flooded in the network. As a third optimization, an MPR node may chose to report only links between itself and its MPR selectors. Hence, as contrary to the classic link state algorithm, partial link state information is distributed in the network. This information is then used for route calculation. OLSR provides optimal routes (in terms of number of hops or link quality). The protocol is particularly suitable for large and dense networks as the technique of MPRs works well in this context.[5]

In order for OLSR to either provide optimal routes utilizing the number of hops or link quality several tables need to be continually updated and maintained. The tables needed for route calculation are based upon received control traffic in the form of three required types of control messages.

Hello – Hello messages, perform the task of link sensing, neighbor detection, and MPR signaling.

Topology Control (TC) – TC messages, perform the task of topology declaration (advertisement of link states).

Multiple Interface Declaration (MID) – MID messages, perform the task of declaring the presence of multiple interfaces on a node.[6]

[5] Clausen, T. and Jacquet, P. *Optimized Link State Routing Protocol (OLSR)*. RFC 3626, Network Working Group, October 2003, 1.

[6] Ibid, 20.

All required control messages are continuously transmitted to all reachable neighboring nodes in a selectable time interval. MPRs assist in controlling and optimizing the use of these control messages.

OLSR is currently available for free download at www.olsr.org. Several hardware and operating system variants are available, as well as variants that utilize various routing schemas as well.

a. OLSR 0.4.7

OLSR 0.4.7 is a pure Request for Comments (RFC)-compliant OLSR that simply uses the minimum number of hops between nodes to determine the routing path for information. The drawback to this routing method is that a single bad link is chosen over a high quality multi-hop route. This poor routing decision is made regardless of link quality. OLSR 0.4.8 is an attempt to resolve this dilemma.

b. OLSR 0.4.8

OLSR 0.4.8 attempts to resolve this dilemma by implementing an Expected Transmission Count (ETX) like metric. OLSR 0.4.8 introduces the idea of utilizing link quality as the determining factor for routing. To solve this problem, we have to teach OLSR how to tell good links from bad links. We have done so by measuring the packet loss for OLSR packets that we receive from our neighbors. As we periodically receive HELLO messages from our neighbors (by default every 2 seconds), we have enough packets to determine the packet loss for packets that each of our neighbors sends to us.

If, for example, three out of 10 packets are lost on their way from our neighbor to ourselves, we have a packet loss of 3/10 = 0.3 = 30%. At the same time, 7 of the 10 packets that the neighbor sent went through. Hence, the probability for a successful packet transmission from this neighbor to ourselves is 7/10 = 0.7 = 70%. This probability is what we call the Link Quality. Therefore, the Link Quality says how good a given link between a neighbor and ourselves are in the direction from the neighbor to ourselves. It does so by saying how likely it is that a packet that we send is successfully received by our neighbor.

However, it is also important to know the quality of the link in the opposite direction, i.e. how many of the packets that we send out are received by each of our neighbors. Therefore, we are not only interested in the Link Quality of a given link, but also in the corresponding neighbor's idea of the Link Quality. That is what we call the Neighbor Link Quality. The Neighbor Link Quality says how good a given link between a neighbor and ourselves are in the direction from ourselves to the neighbor.

The Link Quality and the Neighbor Link Quality are values between 0 and 1 or, which is equivalent, between 0 and 100%. They represent the probability that a packet that our neighbor sends actually makes it to us (Link Quality) and that a packet that we send actually makes it to our neighbor (Neighbor Link Quality).

Let us now look at the probability for a successful packet round trip, i.e. the probability that we successfully send a packet to our neighbor and, on receiving it, our neighbor successfully replies with a response packet. For a successful round trip both packets must get through, the packet that we have sent and the response packet that our neighbor has sent. Therefore, the success probability is Neighbor Link Quality (NLQ) x Link Quality (LQ), where NLQ is the Neighbor Link Quality of the link and LQ is its link quality. For example, if we have a NLQ of 60% and a LQ of 70%, the probability of a successful round trip is 60% x 70% = 0.6 x 0.7 = 0.42 = 42%.

We can now answer the question of how many transmission attempts it will typically take to get a packet from us to a neighbor or from the neighbor to us. It is 1 / (NLQ x LQ). So, in the above case of NLQ x LQ = 42%, we expect on average 1 / 0.42 = 2.38 transmission attempts for a packet until it gets through. The value 1 / (NLQ x LQ) is called the Expected Transmission Count or ETX.[7]

In order to simply things, OLSR 0.4.8 created LQ Hello messages that contain the NLQ. Because we know our LQ and our neighbors send us their NLQ in the newly created LQ Hello messages the ETX is calculated in a simpler manner.

[7] Thomas Lopatic, *OLSRD Link Quality Extensions,* <*http://www.olsr.org/doc/README-Link-Quality.html*>, December 2004, Last Accessed 18 Feb 05, 1.

In addition to LQ Hello messages, OLSR created LQ TC messages. The LQ TC messages provide neighbor lists and their respective link quality for all other nodes in the mesh. This enables the link quality calculation of end-to-end routing to become a reality.

The addition of LQ Hello and LQ TC messages makes OLSR 0.4.8 incompatible with earlier forms of OLSR when ETX is enabled.

2. Reactive Protocols

The family of reactive protocols differs greatly from the proactive protocols in the means of maintaining the routing tables. Reactive protocols only seek routes to destination addresses on-demand. When a destination address is not currently known a reactive protocol will attempt to seek out the route needed to deliver the packets. Reactive protocols tend to have a higher latency issue then that of a proactive protocol. Several examples of reactive protocols that are currently available are Dynamic Source Routing (DSR) and Ad-Hoc On-Demand Distance Vector (AODV).

3. Hybrid and Combination Protocols

It is nearly impossible to develop a perfect protocol that would fit every user situation. However, the developments of hybrid and combination protocols attempts to solve this dilemma by either blending proactive and reactive protocols or devise an alternative method of routing. Examples of hybrid and combination protocols are Zone Routing Protocol (ZRP) and Landmark Ad Hoc Routing (LANMAR).

4. Routing Protocol Summary

My thesis research primarily focused on a proactive protocol, specifically OLSR, but that does not necessarily indicate that it is the best and only solution to mesh networks in a military setting. A hybrid or combination style protocol may be the most logical solution but given the availability and the attributes of OLSR, it was the sensible choice for my thesis research. Many more ad-hoc routing protocols exist and many more are constantly being developed. The following figure is a graphical representation of the numerous other protocols in existence.

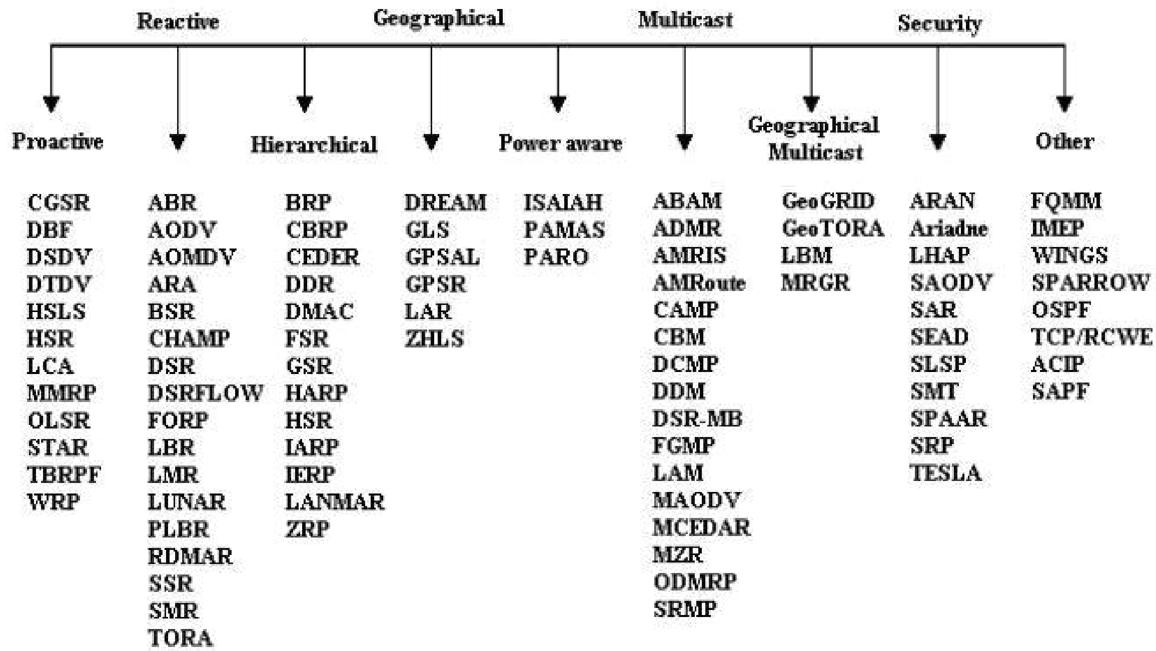

Figure 3. Collection of Known Ad Hoc Routing Protocols (From Halvardsson and Lindberg)[8]

D. ARCHITECTURES

The architectures associated with mesh networks are: fixed, mobile, sensor and a hybrid/mixed mode.[9] The concept of these architecture types were developed logically utilizing geographical positioning and employment.

1. Fixed

In a fixed (geographically speaking) mesh architecture, wireless mesh nodes are typically operated in an access point manner. In this fashion, the mesh access point can provide a means of gaining access to a high-speed backbone that is typically a wired backhaul. The fixed architecture is one of the methods of providing the proverbial "last mile" to the customers in a broadband wireless access solution. The figure below illustrates a geographical fixed mesh network enabling a communications link within a

8 Halvardsson,M. and Lindberg, P. *"Reliable Group Communication in a Military Mobile Ad hoc Network,"* Master's Thesis, Vaxjo University, Vaxjo, Sweden. February 2004, 15.

9 Bach, E.J. and Fickel, M.G., *An Analysis of the Feasibility and Applicability of IEEE 802.X Wireless Mesh Networks Within the Global Information Grid,* Master's Thesis, Naval Postgraduate School, Monterey, California, September 2004, 17.

community of homes. This is also an example of a low cost wireless "last mile" solution for homes with no current infrastructure.

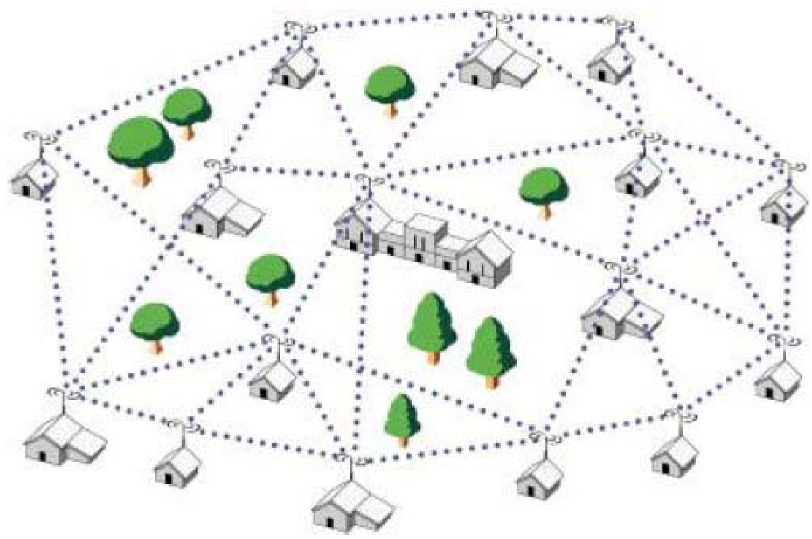

Figure 4. Community Fixed Mesh Example (From Bach and Fickel)[10]

2. Mobile

The idea of a mobile (geographically speaking) node that will have ubiquitous connectivity is the one of the primary reasons to implement a mesh network. A fixed mesh provides a good basis for the "last mile" but the very thought of having the capability to also be mobile and maintain connectivity is an added benefit especially in a military urban environment. In addition to having the ability to move around, mobile mesh networks enable the operator or node to extend the theoretical range of the mesh by utilizing the multi-hop routing function inherent in mesh algorithms. This ability to provide multi-hop routing at each mobile node provides expandability and flexibility not seen in a simple ad-hoc network. The value behind multi-hop routing is the theoretical capability of aligning your nodes in a daisy chain fashion and still have connectivity end-to-end. In this fashion, you are extending the range of the network beyond what is possible in any other architecture. As well as providing an extended network, a mobile mesh will contain alternate routing paths, if available, to provide greater flexibility for movement and operation of the nodes.

[10] Bach, E.J. and Fickel, M.G., *An Analysis of the Feasibility and Applicability of IEEE 802.X Wireless Mesh Networks Within the Global Information Grid,* Master's Thesis, Naval Postgraduate School, Monterey, California, September 2004, 18.

3. Sensor

The principle behind sensor (employment speaking) mesh networks is that of low data rate, long-lived sensors that provide sensor data to a higher level processing power and appropriate applications. This processing device can be considered an aggregation point providing integration and interoperability into the larger network.[11] The raw sensor data provided by sensor mesh nodes require processing external to the sensor nodes thus enabling power conservation and size reduction for the sensors themselves. The style of sensors and data provided by these sensors can range from acoustic to motion detection.

4. Hybrid/Mixed

The hybrid/mixed mesh involve the integration of all three mesh architectures to create a highly capable network. Illustrated below is an example of a hybrid/mixed mesh. This network represents an example of a network testbed used during a Naval Postgraduate School Tactical Network Topology Field Experiment. This example illustrates the successful integration of sensors, highly mobile nodes and a fixed infrastructure. The data transmitted through the mesh can originate as either live video from a camera activated via a motion detection sensor, voice or video from a soldier in an urban environment, or satellite imagery. This information is passed through the mesh in a variety of means via an unmanned aerial vehicle (UAV), high-mobility multipurpose wheeled vehicle (HMMWV), or possibly another soldier. The medium used is 802.11b/g, ultra wideband, iridium, or 802.16. Once this information is at the Camp Roberts Network Operations Center (NOC), the information is processed and sent to the Naval Postgraduate School Global Information Grid Applications Laboratory This critical information is transferred to the final destination of Lawrence Livermore Laboratories (LLNL), FT Meade, FT Bragg, or Special Operations Command (SOCOM) for final processing and decision-making. This brief example illustrates the powerful potential that exists in deployment of mesh network technology.

[11] Bach, E.J. and Fickel, M.G., *An Analysis of the Feasibility and Applicability of IEEE 802.X Wireless Mesh Networks Within the Global Information Grid,* Master's Thesis, Naval Postgraduate School, Monterey, California, September 2004, 28.

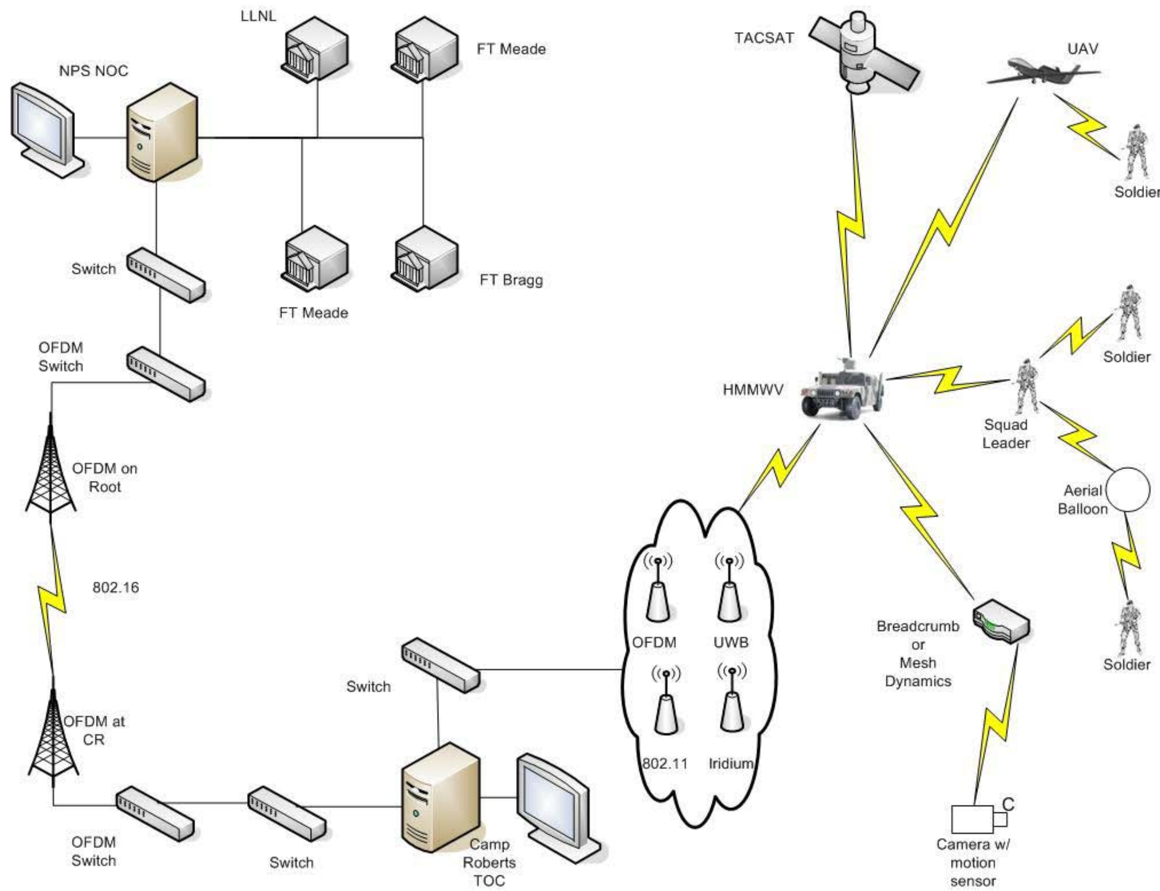

Figure 5. Example of a Hybrid/Mixed Mesh

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III. ULTRA WIDEBAND TECHNOLOGY

In simple terms, ultra wideband (UWB) transmitters send billions of coded, sequenced, extremely narrow pulses in specific timing across a very wide frequency spectrum. The bandwidth of this transmission can be several GHz wide. The Federal Communications Commission (FCC) has defined that UWB transmissions fall within the frequencies of 3.1 to 10.6 GHz, with a minimum spectral width of 500 MHz, or 25% of the center frequency (3.5 to 4.5 GHz for a center frequency of 4 GHz).[12] The corresponding receiver, knowing the sequence and timing of the pulses, translates the received pulses into data. Narrowband technology, on the other hand, has a typical bandwidth of 10% or less. For instance, 802.11b has a bandwidth of 22MHz with a center frequency in the range of 2.4GHz.

A. BRIEF HISTORY

A form of UWB technology has been in existence for a very long time. Guglielmo Marconi in the late 1800's was the first to utilize this technology to transmit Morse code using his Spark Gap radio. Spark gap technology remained dominant until narrowband (continuous wave) radios arrived and provided a better solution for voice communications in the early 1900's. It was not until the early 1970's that UWB technology re-emerged and was referred to as baseband, carrier-free, or impulse technology. In 1989, the Department of Defense ultimately applied the term "ultra wideband".[13] On April 22, 2002, the FCC issued UWB Regulations, under Part 15 of the Commission's rules, permitting ultra-wideband intentional emissions subject to certain frequencies and power limitations that will mitigate interference risk to those sharing the same spectrum.[14]

B. CHARACTERISTICS

Several characteristics, other than just the frequency bandwidth, set UWB apart from traditional narrowband or spread spectrum signals.

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[12] Cravotta, N., *Ultrawideband: the next wireless panacea?* (17 October 2002). Electronic resource available from <http://www.edn.com/article/ca250832.html>, Last Accessed 19 Feb 05.

[13] Wilson, J. M., *Ultra-Wideband/a Disruptive RF Technology?* (10 September 2002). Electronic resource available from <http://www.intel.com/technology/comms/uwb/download/Ultra-Wideband_Technology.pdf>, Last Accessed 19 Feb 05, 3.

[14] Ibid, 4.

1. Output Power

The power of a UWB signal is spread across the entire frequency bandwidth that is being employed. UWB uses extremely short pulses with a very low duty cycle or ratio of a pulses presence to the total transmission time. Because of this low duty cycle, the average transmission power of UWB is very low. When I mention low, I imply in the micro or nanowatts. In comparison, a cell phone transmits over 1000 times the level of UWB.[15] The average transmission power is so low it falls below the noise threshold. For example, 1W of total power spread across 1 GHz of frequency spectrum puts only 1nW of power into each hertz band of frequency. This inherent characteristic of transmitted power that falls below the noise threshold/floor (the amplitude in a frequency domain instrument below which the presence of a signal will not be measurable or discernible) makes detection of UWB signals very difficult. In addition, because UWB transmits at such a low power and can vary transmit power based on the distance between nodes and access points, power consumption is minimized and therefore battery life is longer than typical narrowband devices. Narrowband devices consume larger amounts of power because of the requirement of a continuous wave transmission.

2. Data Rate

Shannon's Law helps clarify why UWB is able to provide such a high data rate. Shannon's Law states that the potential data rate over a given radio frequency link is proportional to the bandwidth of the channel and the logarithm of the signal-to-noise ratio.[16] Relative to UWB, narrowband or spread spectrum signals are very limited in the amount of bandwidth permitted as graphically depicted below.

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[15] Nekoogar, F., *Ultra-Wideband Communications-Fundamentals & Applications. Prentice Hall, 2005, 6.*

[16] Intel, *Ultra-wideband (UWB) Technology. Enabling high-speed wireless personal area networks.* (February 2004). Electronic resource available from <http://www.intel.com/technology/comms/uwb/download/ultra-wideband.pdf>, Last Accessed 19 Feb 05, 4.

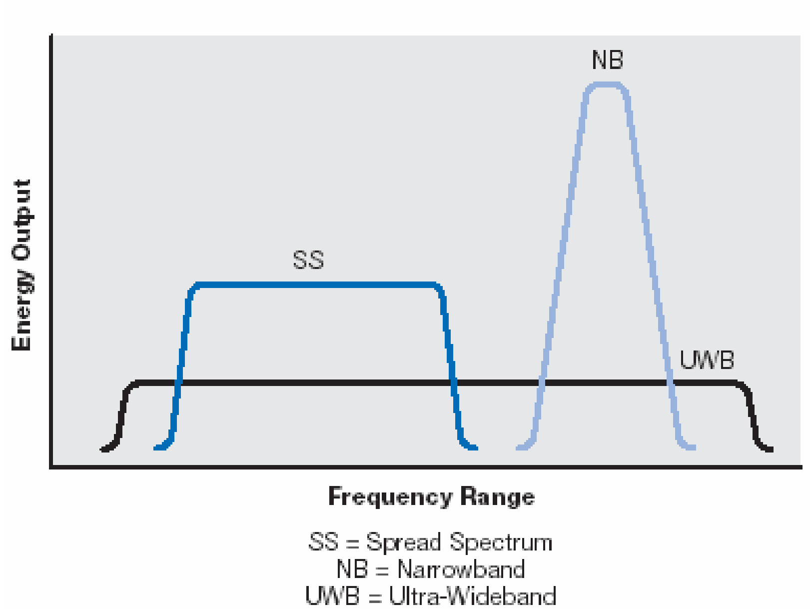

Figure 6. Example of UWB, Narrowband, and Spread Spectrum Frequencies (From Intel)[17]

This added bandwidth enables UWB to provide extremely high data rates. An example is the Wireless Universal Serial Bus (USB) Working Group's recent announcement that a UWB Wireless USB will be able to provide speeds up to 480 Mbps at 10 meters.[18] Although bandwidth is very influential in determining data rates: distance, power and other factors exist that also affect UWB data rates.

C. CAPABILITIES

Due to the inherent characteristics of UWB, several key capabilities arise. These capabilities make UWB technology a good fit for military applications.

1. Covertness

As discussed earlier, the output power of an UWB signal will fall below the noise threshold at a certain distance from the transmitter, making it extremely difficult to detect. This provides UWB with a low probability of detection (LPD). In the event an individual is within range to detect the UWB signal, they must know the coding or timing sequence of the signal to extract any form of information. This unique coding or timing

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1717 Intel, *Ultra-wideband (UWB) Technology. Enabling high-speed wireless personal area networks.* (February 2004). Electronic resource available from <http://www.intel.com/technology/comms/uwb/download/ultra-wideband.pdf>, Last Accessed 19 Feb 05, 4.

18 Ibid, 5.

of the UWB pulses provides UWB's low probability of intercept (LPI) capability. The figure below illustrates how a UWB signal compares with narrowband and spread spectrum signals and where the typical noise threshold might fall.

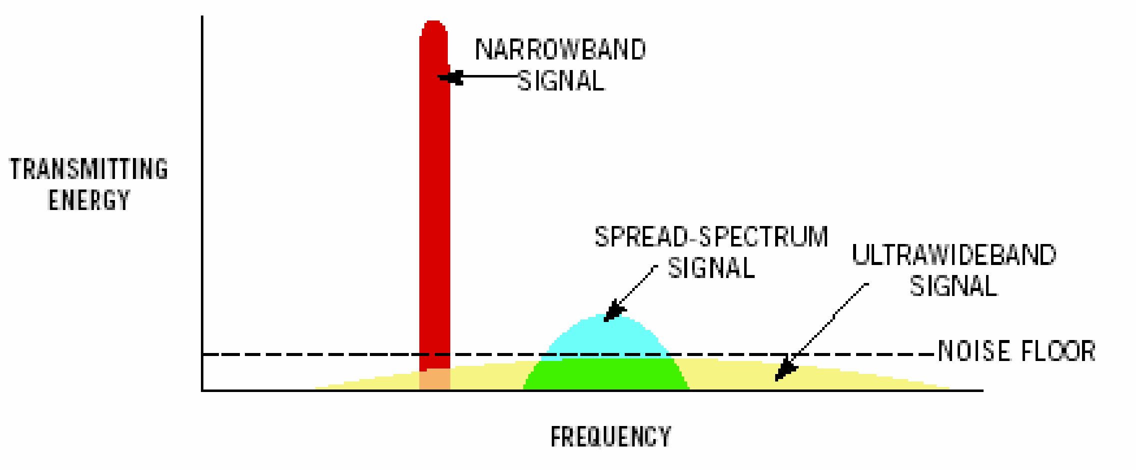

Figure 7. Signal Comparison Against Noise Threshold (From Cravotta)[19]

Making the UWB signal appear as noise is actually a more complex process. For example, if you put out pulses at a regular interval, or pulse-repetition frequency (PRF), you could raise the noise floor on certain carriers and their harmonics. The signal needs to mimic white noise, which is random. Additionally, if you put pulses into more than a certain percentage of windows (some experts say more that 10%), your signal cannot generate enough pseudorandsomness to appear as noise.[20]

2. Fading and Multipath Interference Immunity

Another key advantage of UWB is its robustness to fading and interference. Fading can be caused when random multipath reflections are received out of phase causing a reduction in the amplitude of the original signal. The wideband nature of UWB reduces the effect of random time varying amplitude fluctuations. Short pulses prevent destructive interference from multipath that can cause fade margin in link budgets. However, another important advantage with UWB technology is that multipath components can be resolved and used to improve signal reception. UWB also promises

[19] Cravotta, N., *Ultrawideband: the next wireless panacea?* (17 October 2002). Electronic resource available from <http://www.edn.com/article/ca250832.html>, Last Accessed 19 Feb 05.

[20] Cravotta, N., *Ultrawideband: the next wireless panacea?* (17 October 2002). Electronic resource available from <http://www.edn.com/article/ca250832.html>, Last Accessed 19 Feb 05.

more robust rejection to co-channel interference and narrowband jammers showing a greater ability to overlay a spectrum presently used by narrowband solutions.[21]

3. Penetration Effects

An UWB transmitter transmits in all frequencies within its specified frequency bandwidth. Depending upon the selected bandwidth frequency, UWB may contain lower frequencies, which have longer wavelengths. These longer wavelengths enable UWB transmissions to penetrate structures. Examples of penetrable structures are; concrete walls, dense tree lines, layers of rock and even water.

4. Positioning

Position and location detection is another capability of UWB. UWB is a form of RADAR (Radio Direction and Ranging). Positioning and locating were early focuses of wideband research and development. Short impulses (wideband signal) allow for very accurate delay estimates providing position and location capabilities within a few centimeters.[22]

D. EXISTING SYSTEMS

Currently there are many applications of UWB technology deployed in military and civilian arenas. Some of the industry leaders in the UWB technology field are Intel, Geozondas, Multispectral Solutions Inc, Time Domain, and LLNL. The following are just a few brief examples of systems currently available.

1. Surveillance Systems

UWB can operate as a security fence. UWB can establish a stationary radio frequency (RF) perimeter fencing that will detect any intrusion by personnel or objects.

2. Ground Penetrating Radar and Imaging Devices

Ground Penetrating Radar (GPR) is an ultra-wideband imaging technique used for subsurface exploration and monitoring. It is widely used for locating utility lines; monitoring pavement, runways, and walls for soundness and thickness; archaeology; forensic examinations; mining, ice sounding, detecting unexploded land mines and

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[21] Wilson, J. M., *Ultra-Wideband/a Disruptive RF Technology?* (10 September 2002). Electronic resource available from <http://www.intel.com/technology/comms/uwb/download/Ultra-Wideband_Technology.pdf>, Last Accessed 19 Feb 05, 5.

[22] Ibid, 6.

bombs,; agricultural; groundwater studies; permafrost, void, cave and tunnel detection, location of sinkholes, subsidence, and many other similar applications.

The beauty of GPR is that it is non-invasive, relatively inexpensive, and can be used in a variety of ways -- there are hand-held units, downhole units, units that can be dragged behind vehicles, and even from aircraft and satellites. It has the highest resolution of any subsurface imaging method (sometimes with resolutions of one centimeter), and is far safer than x-ray technology.[23] Imaging systems, used in the same manner as a GPR, will enable police, fire and rescue personnel to locate persons trapped or hidden beneath debris in a crisis situation. The figure below is an example of a ground penetrating radar.

Figure 8. Ground Penetrating Radar (From Geozondas)[24]

[23] Spread Spectrum Scene, "*Ground Penetrating Radar*". Available from <http://www.sss-mag.com/gpr.html#news>. Last Accessed 20 Feb 05.

[24] Geozondas, "UWB *Ground Penetrating Radar GZ6*". Available from <http://www.geozondas.com/Gz6/gz6.htm>. Last Accessed 20 Feb 05.

3. Communication Transceivers

The figure below illustrates an example of a handheld UWB communications device. The device in this example provides full duplex voice and data transmission rates up to 128 kb/s. The approximate range of these handhelds are 1 to 2 kilometers (with the small antennas shown and line of sight), and an extended range of 10 to 20 kilometers with small gain antennas.

Figure 9. Full Duplex Handheld UWB Transceiver (From Fontana) [25]

4. Geolocation System

The figure below illustrates a system designed to provide 3-dimensional location information utilizing a set of untethered UWB beacons and an untethered, mobile UWB rover. Precision location is derived from round trip, time-of-flight measurements using packet burst transmissions from the UWB rover and beacon transponders. Line-of-sight range for the system is better than 2 kilometers utilizing small, omnidirectional vertically polarized (smaller) or circularly polarized (larger) antennas. Within a building, the range becomes limited by wall and obstacle attenuation; however, ranges exceeding 100 meters inside have been attained. A unique feature of the system is the ability to detect the pulse leading edge through the use of a charge sensitive, tunnel diode detector. Leading edge detection is critical to the resolution of the direct path from the plethora of multipath returns produced from internal reflections. The UWB geolocation system was originally developed to permit a soldier to determine his or her position to within 1-foot resolution

[25] Fontana, R. J., *Recent Applications of Ultra Wideband Radar and Communications Systems.* Electronic resource available from <http://www.multispectral.com/pdf/UWBApplications.pdf>, Last Accessed 19 Feb 05, 3.

in an urban environment. It is currently being used to augment a video capture system for 3-D modeling and for materiel location onboard a Navy ship.

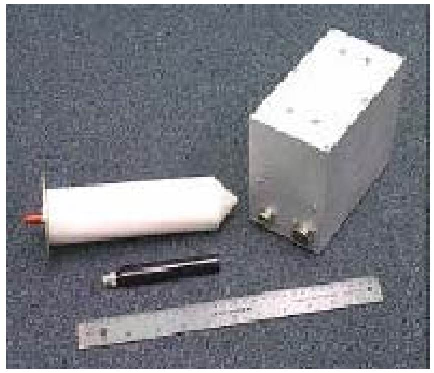

Figure 10. UWB Precision Geolocation System Tranceiver (From Fontana)[26]

E. JOINT RESEARCH WITH LLNL

Presently, the field of UWB technology has not developed into a mature industry. The corporate world has provided a very limited amount of advances in UWB technology with only a few systems available. LLNL has been developing UWB technology for potential military applications. LLNL has a long history of collaborating with the DoD and other government agencies to provide research and development support to meet emerging national security needs. LLNL has experience and expertise in many areas of science and technology directly relevant to defense needs. LLNL's location and proven history of technological advances made them the ideal partner is NPS's joint research in the arena of UWB.

[26] Fontana, R. J., *Recent Applications of Ultra Wideband Radar and Communications Systems.* Electronic resource available from <http://www.multispectral.com/pdf/UWBApplications.pdf>, Last Accessed 19 Feb 05, 6.

IV. EXPERIMENTAL RESULTS

A. TACTICAL NETWORK TOPOLOGY (TNT) FIELD EXPERIMENTAL GOALS AND APPROACHES

The NPS TNT Field Experiments is a series of field experiments to test various network component technologies for interoperability in a tactical environment. TNT employs various high-speed ground, underwater, and air assets to examine the most recent innovations and designs in network technology. The figure below is the NPS's TNT Comprehensive Diagram.

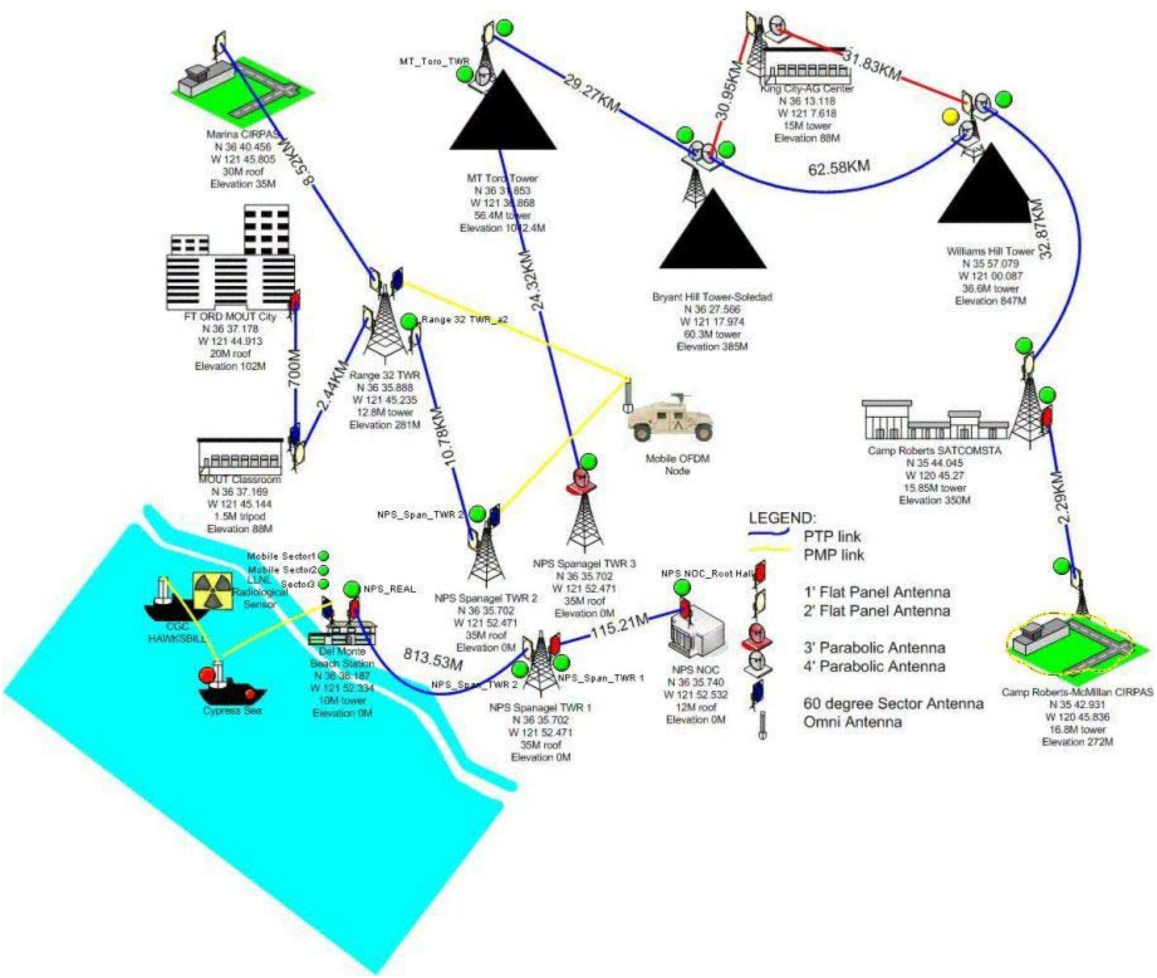

Figure 11. NPS's TNT Comprehensive Diagram

The TNT comprehensive diagram illustrates the wireless backbone that provided the ubiquitous connectivity between the Tactical Operations Center located at Camp Roberts, CA, the Network Operations Center located at the NPS in Monterey, CA and the various highly mobile operational nodes in the air, at sea and in the field .

B. TACTICAL NETWORK TOPOLOGY 05-1

NPS's TNT 05-1 was conducted November 15-23, 2004, at Camp Roberts, CA and the Naval Postgraduate School in Monterey, CA. This was the first iteration of the quarterly recurring series of field experiments held by NPS. The overarching goals of TNT 05-1 were to conduct field experiments with a collection of networking components to ascertain, establish, and improve the situational awareness on the battlefield.

1. Objectives

Within the larger TNT framework, the UWB and Collaboration objectives encompassed two areas of interest.

a. Ultra Wideband Through-Wall Performance

Evaluate the potential of the LLNL UWB test set on its capability to establish a successful UWB communications link through concrete walls.

b. Collaboration of Ultra Wideband Performance

Test the ability of the Situation Awareness (SA) and Groove programs to provide adequate UWB video information to all participants in the network.

c. 802.11b Mesh Performance for UWB Video

Demonstrate the ability of an 802.11b mesh network to provide connectivity for the UWB video routing to the Network Operations Center (NOC).

2. Experimentation

The experiment was conducted at NPS in both Halligan and Root Halls. The ultimate goal was the successfully delivery of UWB streaming video through multiple walls in the basement of Halligan Hall across the NPS Quad via an 802.11b mesh network to the Root Hall Gigalab NOC for collaboration with Ft Bragg, NC and Tampa, FL.

a. UWB Experiment Details

The diagram below illustrates the prototype UWB test setup constructed by LLNL. The setup consisted of an UWB transmitter and receiver set transmitting live streaming video of a passageway through multiple walls. The distance between the transmitter and receiver was approximately 56 feet. The transmission penetrated two walls and across three rooms. The first wall to be penetrated was constructed of 10-inch reinforced concrete and the second wall was 6 inches of sheetrock with metal studs. The transmitter for this experiment was transmitting in a frequency range of 1.2 – 1.6 GHz at a 2 mW average total power output.

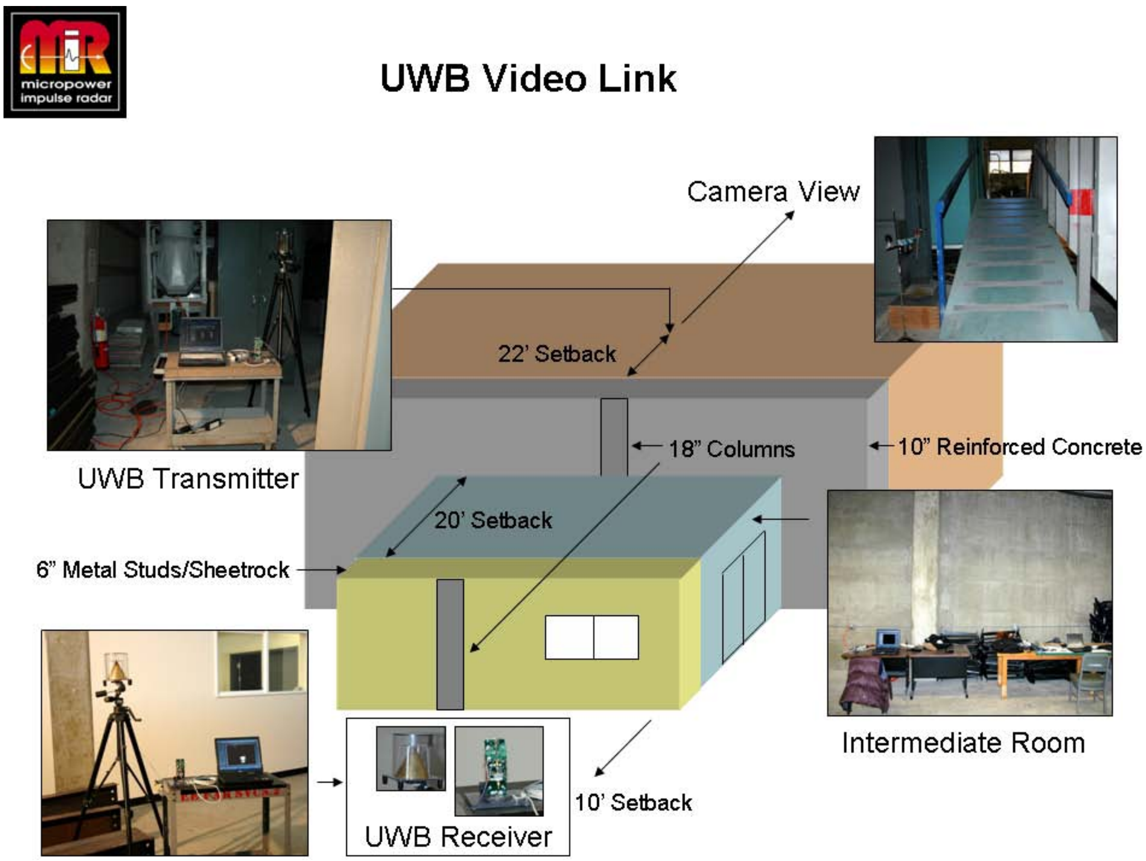

Figure 12. UWB Test Setup in Halligan Hall

The next illustration is another view of the UWB receiver used in the experiment. The distances traveled, the throughput achieved and the obstacles that the UWB transmissions were able to penetrate successfully demonstrated that UWB technology is a viable physical layer medium. This physical link will have a great impact in a tactical operational environment. The UWB transmitter is very similar in appearance to the UWB receiver.

Figure 13. UWB Receiver Set

b. Collaboration Experiment Details

The collaboration effort was conducted utilizing the NPS Situational Awareness program and Groove. The NPS SA program is a collaboration program that provides real time information on preloaded charts. Some of the useful information provided is position data, real time video, messaging, network monitoring, and event posting. Groove is a COTS software collaboration tool that provides file sharing, event tracking, communications via chat or messaging, and numerous other useful items. Both tools were employed for this experiment.

c. 802.11b Mesh Experiment Details

The UWB video was delivered to the Gigalab NOC on an 802.11b mesh network. The figure below gives an overview of the network topography.

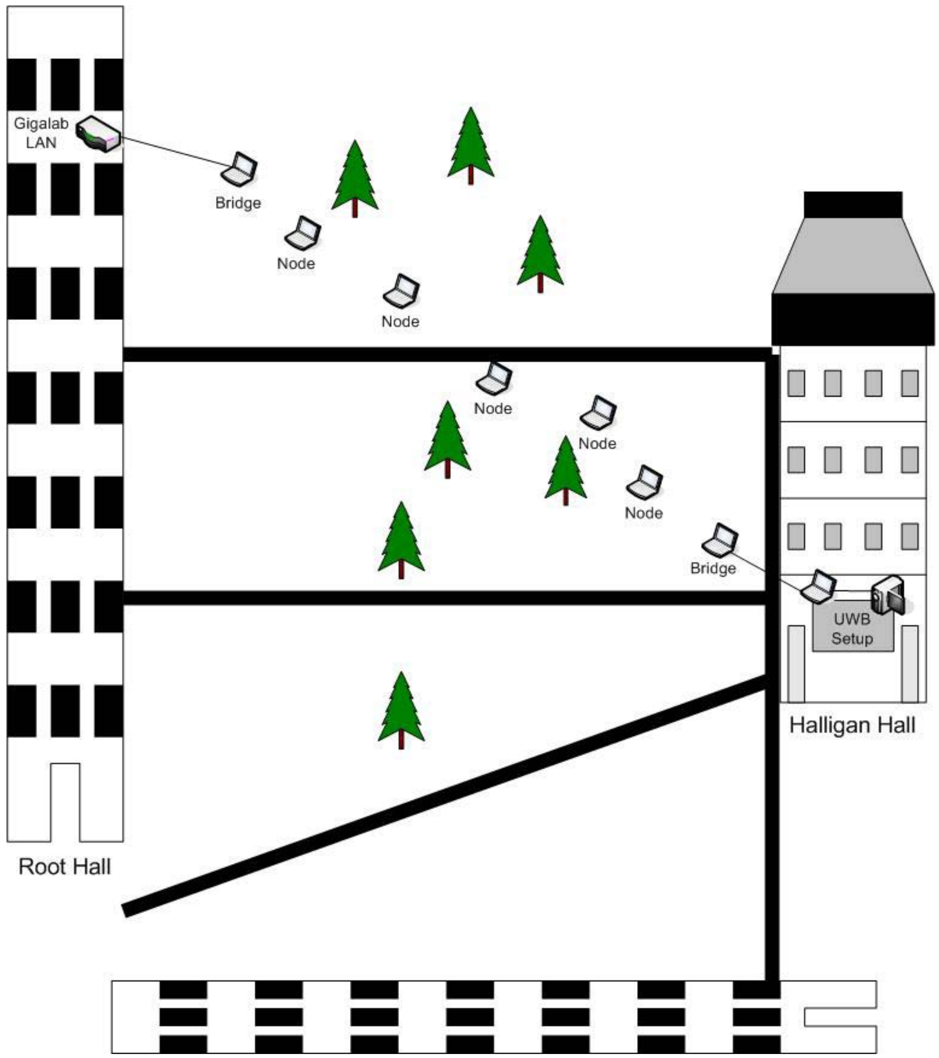

Figure 14. NPS UWB Test Network Topography

This simplified illustration of the mesh network shows the intermediate nodes, bridges (join points), and UWB equipment that was used during the experiment in the NPS quad. The intermediate nodes, bridges, and server configurations were as follows:

- Dell Latitude X300, 1.4 GHz Pentium M processor, 632 MB Random Access Memory (RAM) and an Orinoco Gold 802.11b/g Wireless Personal Computer Memory Card International Association (PCMCIA) Network Interface Card (NIC) running at 100% transmit power. The operating systems were Windows XP Professional. The mesh protocol used was OLSR 0.4.7. (Intermediate Nodes/Bridges)
- Dell Dimension 4500, 2.4 GHz Pentium 4 processor and 1 GB RAM. The operating system was Windows Server 2003. (Gigalab NOC/LAN)

There existed five Mesh intermediate nodes with two Mesh bridges connecting the Global Information Grid Applications Lab (Gigalab) Local Area Network (LAN) and the UWB test set with the 802.11b mesh network. The distances between nodes and bridges were approximately 50 feet. The amount of Ethernet cable used between the bridges and the Gigalab LAN and the UWB test set was approximately 150 feet.

3. Results

The results were measured a success if video was successfully transferred to their end users in a timely fashion without unnecessary delays.

a. UWB Results

The illustration below gives a more detailed picture of the UWB receiver set and an example of the successfully transmitted video stream. The video presents an individual walking down the passageway beyond the obstacles. The UWB received data for the video stream was presented on a laptop. Due to interface issues, the UWB data stream could not be directly transmitted over the 802.11b mesh. A separate laptop with a Canon VC-C4 video camera took live video of the UWB display that was then transmitted over the 802.11b mesh to the Root Hall Gigalab NOC for further use on the Situation Awareness Program.

Figure 15. UWB Video Display

b. Collaboration Results

The results were very positive; video was received successfully at Ft Bragg, NC, Tampa, FL and the Gigalab NOC.

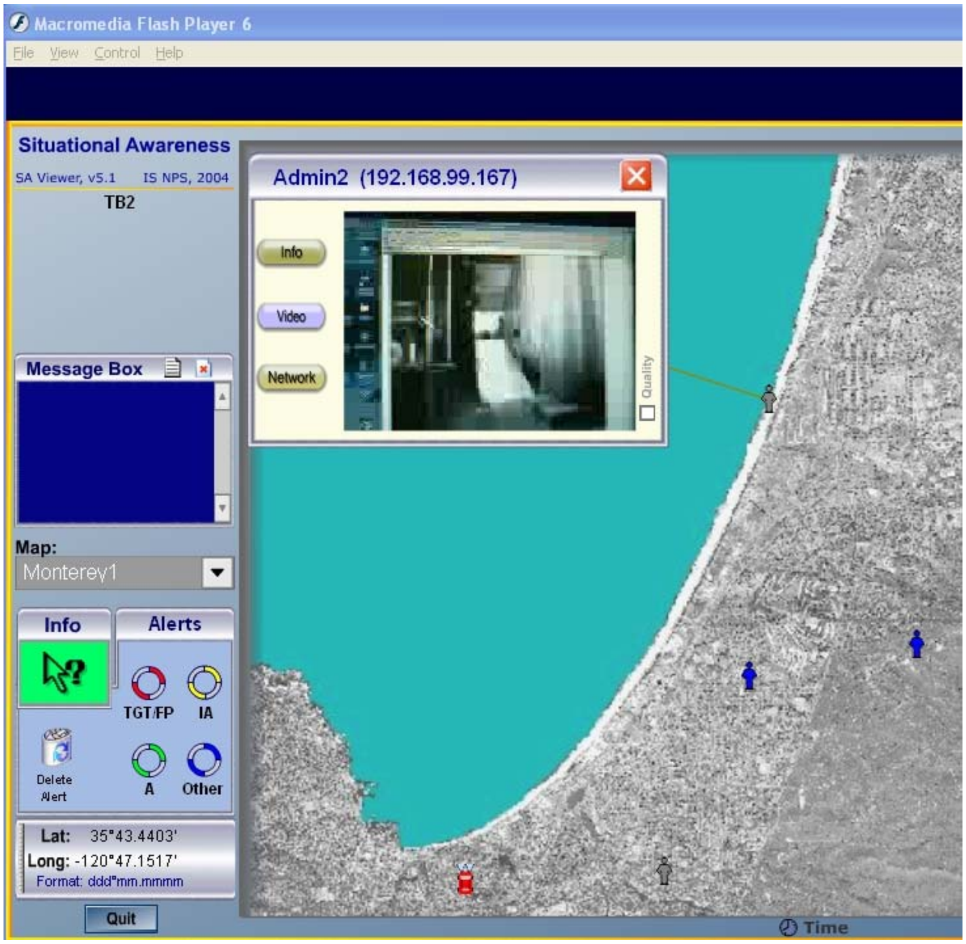

Figure 16. SA View of UWB Video

The above screen shot represents the five nodes in the Situational Awareness Program. The table below is a breakdown of the nodes represented in the SA program.

Node	Symbology	Geographic Location
NOC	Red Vehicle	NPS Gigalab
Admin2	Grey Individual to North	NPS Halligan Hall Basement
Ft Bragg	Blue Individual to East	Ft Bragg, NC
Tampa HQ	Blue Individual to West	Tampa, FL
Admin1	Grey Individual to South	NPS Gigalab

Table 1. SA Node Representation for TNT 05-1

The UWB video stream of the passageway in the Halligan Hall basement is presented by Admin2 on the Situational Awareness Program from the UWB test set. This video was being projected on a video screen in the Gigalab by Admin1. The video rode on the 802.11b mesh backbone from Halligan Hall to the Gigalab in Root Hall. The video was then made available to Ft. Bragg and Tampa via the open source internet.

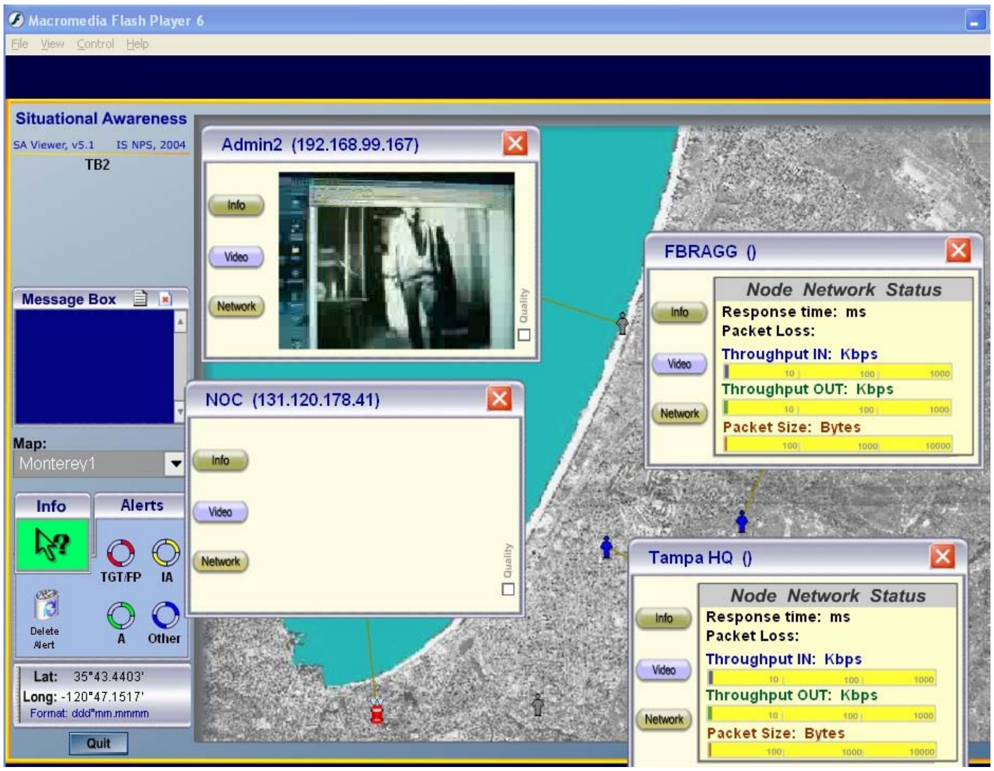

Figure 17. SA View with Collaboration

The above illustration displays an individual proceeding down the passageway. The FT Bragg and Tampa SA nodes helped demonstrate the ability of the SA program to successfully collaborate with remote sites over 3000 miles away in real time. The UWB video stream was being observed at FT Bragg, NC and in Tampa, FL. A chat session was also being operated concurrently with the video stream using the SA program. The SA program also has the ability to perform network monitoring. Unfortunately, during the exercise, the Simple Network Management Protocol (SNMP) agent was not activated that would have provided the performance data necessary to populate the network monitoring fields.

c. *802.11b Mesh Results*

The 802.11b mesh network performed adequately in support of the video transfer. The figure below helps point out some of the network characteristics captured utilizing the Solarwinds Program.

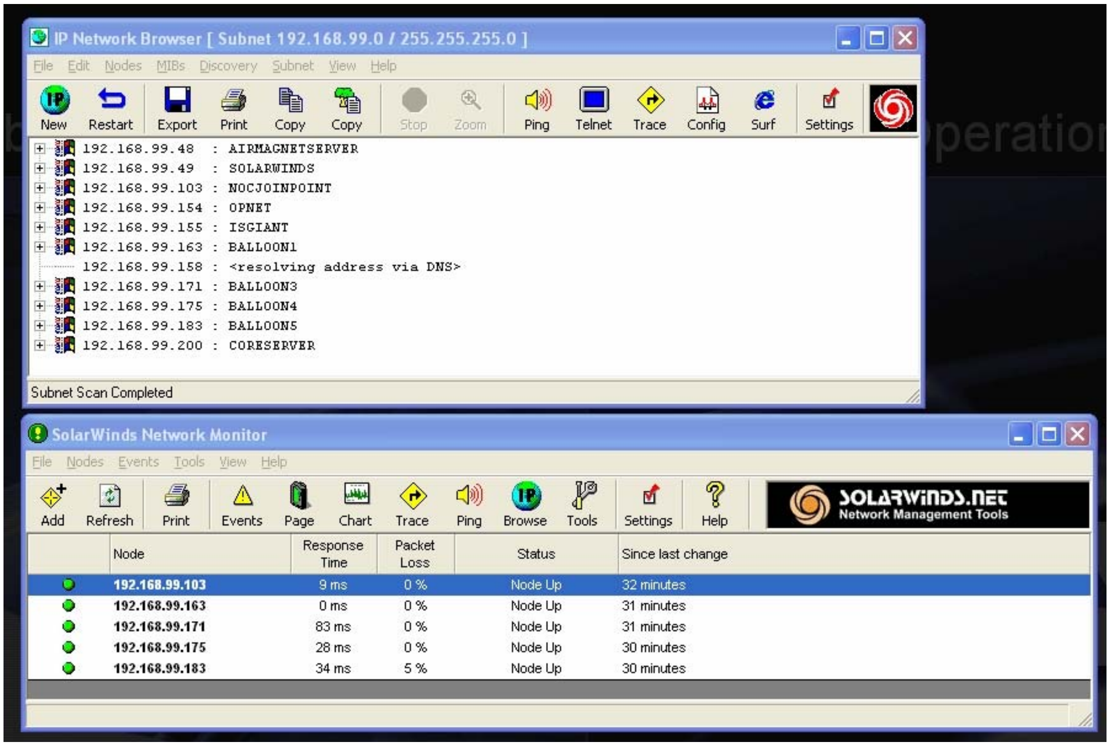

Figure 18. Mesh Network in Solarwinds

Both join points and several intermediate nodes were being monitored. The response time and packet loss encountered were satisfactory. The mesh did have trouble if the nodes were stretched to their maximum ranges. Because of this, we placed the intermediate nodes in a manner that ensured that redundancy and alternate paths were available if the primary links were ever dropped during the experiment. Despite the difficulties, the throughput range observed during the experiment ranged from 6 kb/s – 180 kb/s.

4. TNT 05-1 Conclusions

The experiment with the UWB transmitter and receiver set proved to be an overwhelming success. The UWB data penetrated the walls in Halligan Hall’s basement and was successfully displayed on the LLNL laptop. The 802.11b mesh performed satisfactorily. The problems encountered with the 802.11b mesh will need further testing and research to determine the possible causes for insufficient routing and link quality. The collaboration tools utilized also performed extremely well. The SNMP agents in the SA program will be activated in further experiments.

C. TACTICAL NETWORK TOPOLOGY 05-2

NPS's TNT 05-2 was conducted February 22, 2005 – March 4, 2005, at Camp Roberts, CA and the Naval Postgraduate School in Monterey, CA. This was the second iteration of the quarterly recurring series of field experiments held by NPS. The overarching goals of TNT 05-2 were to conduct field experiments with a collection of networking components to ascertain, establish, and improve the situational awareness on the battlefield.

1. Objectives

Within the larger TNT framework, the Mesh, UWB and Collaboration objectives encompassed four areas of interest.

a. Collaborative Tool Performance in a Mesh Network

The objective is to utilize the Situational Awareness program to test the potential of improved tactical awareness for the operators in the NOC and Tactical Operations Center (TOC) with eventual dissemination of information to the troops on the ground using various sensors and video images broadcast through the mesh.

b. 802.11 Mesh Performance

The traditional 802.11b laptop mesh utilizing OLSR 0.4.7 that was used in TNT 05-1 provided an adequate link for the UWB video to reach the Gigalab NOC. The objective of this experiment was to test an alternative means of 802.11 wireless mesh. In conjunction with MeshDynamics, we established an 802.11 link utilizing the MeshDynamics structured mesh modules. The figure below is an image of a structured mesh module.

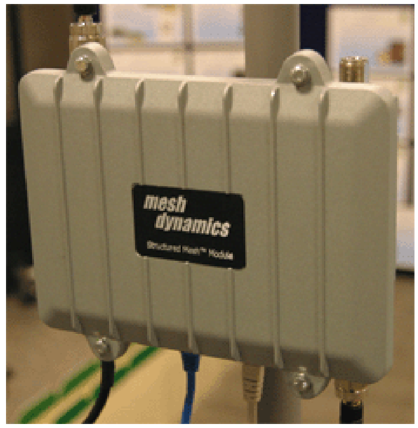

Figure 19. MeshDynamics Structured Mesh Module (From MeshDynamics)[27]

The MeshDynamics structured mesh modules used for this experiment had the following features:

- Dimensions: 8” x 6” x 2”
- Voltage: 6-28 VDC supplied through Ethernet (POE)
- Power: 5-12 Watts, depending on number of radios used
- Processor: Intel XScale IXP42x Processor 533 MHz
- Peripherals: 4 Type III mini-PCI slots
- Memory: 128 Mb RAM, 32 MB SDRAM
- Ethernet: Two 10/100 Base-TX Ethernet Ports
- Serial: Two RS232 ports
- OS: Micro Linux Version 2.4.24
- Radio Cards: Atheros a/b/g mini-PCI cards

The hypothetical improved performance from the MeshDynamics structured mesh modules are based on the idea of employing four radios in each node. The first radio is a dedicated service radio that provides clients access into the mesh network. The service radio operates on its own 802.11b/g channel in infrastructure mode.

27 MeshDynamics, “Structured Mesh Multi-Radio Modules,” <http://www.meshdynamics.com/MDProductNRadio.html>, Last Accessed 3 March 2005.

Next, two dedicated backhaul radio's (one uplink and a separate downlink) operate on separate non-interfering channels in a different band, 802.11a. Finally, the last radio is a scanning radio that monitors the mesh network and ensures that the radio-antenna subsystems are functioning properly. The performance of the MeshDynamics structured mesh is enhanced by using separate non-interfering backhaul channels that provide data transfer while avoiding co-channel interference common to standard one radio communications found in most other 802.11 mesh networks undertaken in the past. The addition of another separate channel for servicing additional mesh clients also greatly enhances the performance of the mesh. The figure below helps illustrate the concept of employing three radios over just one.

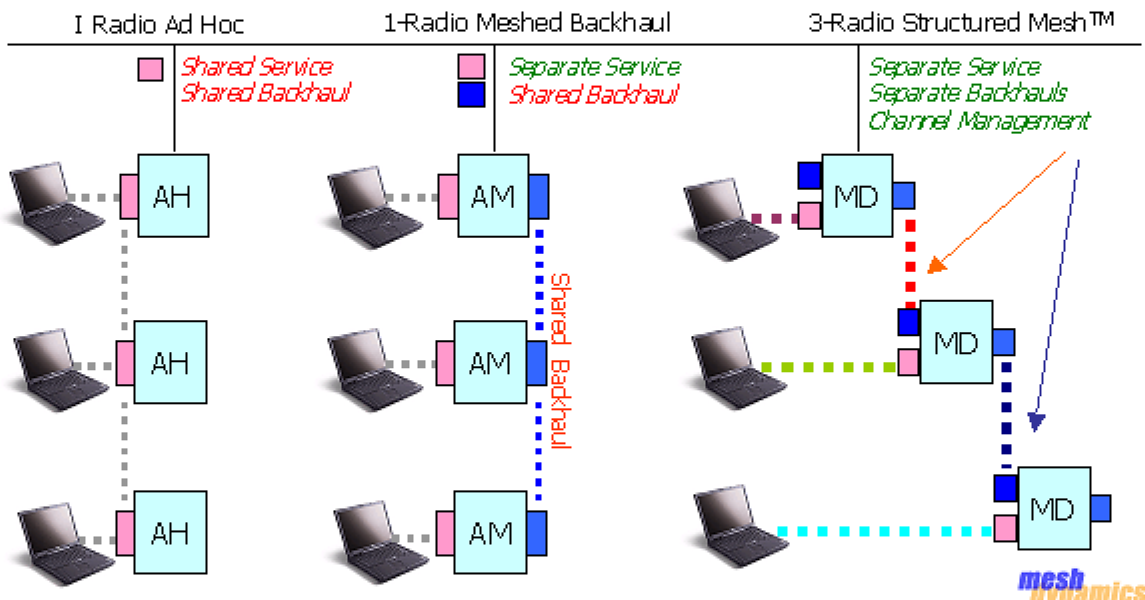

Figure 20. Comparing Structured Mesh with Other Mesh Architecure (From MeshDynamics)[28]

As you can see in the above diagram, there are multiple paths for information to flow to and from the mesh modules and client nodes. This is the enabling factor for higher performance in the structured mesh. I believe the use of the structured mesh concept will enhance the 802.11 backhaul link from Halligan Hall to the Gigalab NOC in Root Hall.

28 MeshDynamics, "Why Structured Mesh is Different," <http://www.meshdynamics.com/WhyStructuredMesh.html>, Last Accessed 3 March 2005.

c. Ultra Wideband LPI/LPD Performance

The objective of the experiment is to determine the approximate distances that the UWB transmitter might be susceptible to interception and detection. A graphical representation of a standard narrowband signal will be compared with a UWB signal.

d. Ultra-Wideband Radar Performance

The objective is to test the performance of the LLNL UWB through-wall radar detection system (Urban Eyes). The video from the Urban Eyes will be integrated into the SA program to enhance tactical awareness.

2. Experimentation

The experiment was conducted in Halligan Hall, Root Hall, and in the quad area located in between Halligan and Root Halls. The experiments provided a means of testing the UWB video data link to support collaboration, MeshDynamics structured mesh network, and the Urban Eyes.

a. Mesh Network Collaborative Tool Experiment Details

The Situational Awareness program will be monitoring the video provided by the UWB data link and the Urban Eyes. The video camera and UWB transmitter will be positioned in the basement of Halligan Hall. The video will be transmitted from the basement of Halligan Hall to a classroom on the first floor of Halligan Hall approximately 300 feet away. The UWB signal will be passing through numerous concrete reinforced walls, sheet rock walls, metal interlaced cementitious walls, and the concrete floor. A motion detection sensor similar to one mounted on the tripod illustrated below will trigger the video camera.

Figure 21. LLNL Motion Detection Sensor

Once triggered, the video camera will supply streaming video to the UWB transmitter. The UWB transmitter for this experiment was transmitting in a frequency range of 200 – 500 MHz at a 400 mW average total power output. The UWB transmitter utilized in TNT 05-2 differed from the transmitter in TNT 05-1. This transmitter was intended to provide a secure communications link with an extended range and greater penetration capabilities. The transmitted UWB signal will be received by the UWB receiver located in the upstairs classroom and then integrated into the SA program. The picture below illustrates the UWB receiver and the video to be input into the SA program.

Figure 22. Video from UWB Communications Link

The LLNL Urban Eyes will be monitoring an adjacent classroom also located in Halligan Hall. An individual will be located in the room bordering the Urban Eyes test set. This individual will be monitored by the Urban Eyes and will provide movement and respiratory functions for the experiment. The video output will also be integrated into the SA program.

b. 802.11 Mesh Experiment Details

The backhaul from Halligan Hall to Root Hall will be provided by the MeshDynamics structured mesh network. The mesh modules were placed in a manner illustrated in the figure below.

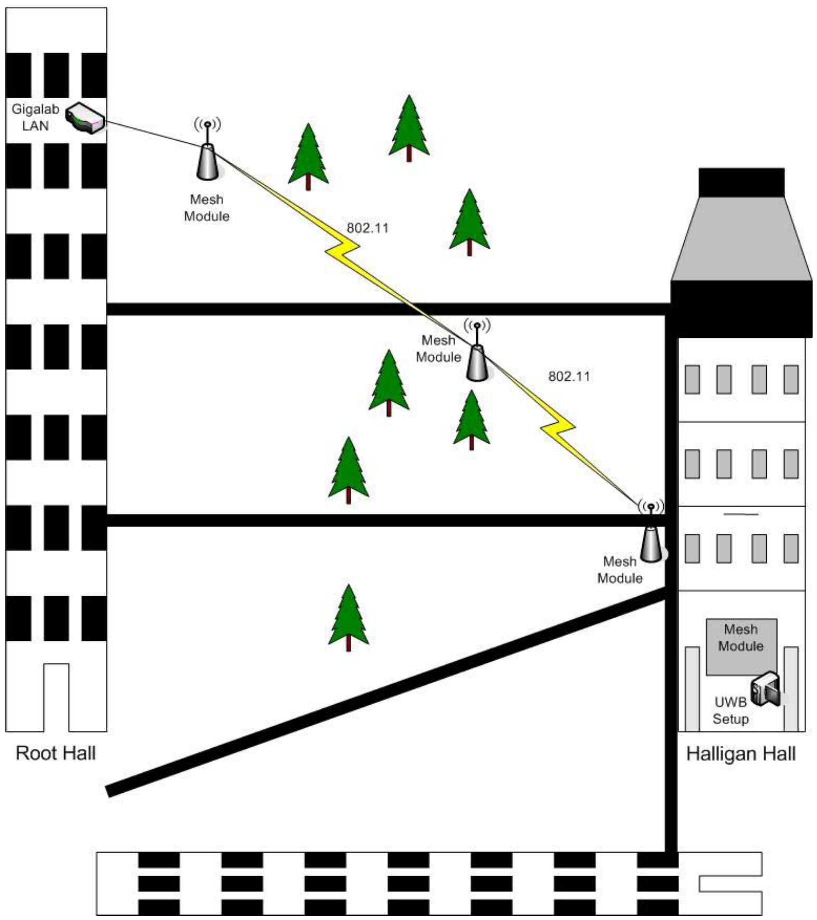

Figure 23. MeshDynamics Structured Mesh Network in NPS Quad

Three mesh modules were primarily utilized. The fourth module was also intermittently online. The mesh modules provided access to the Gigalab network by all client nodes operating the SA program.

c. Ultra Wideband LPI/LPD Experiment Details

The LPI/LPD experiment work was conducted under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratories under Contract Number W-7405-Eng-48. The results were provided to the author by LLNL.

d. Ultra-Wideband Radar Experiment Details

The variant of the Urban Eyes through-wall motion detector used contained two transmitters in the 900 MHz - 3 GHz frequency range with an average total transmit power of 1 mW. The figure below contains the two transmitters used by the Urban Eyes.

Figure 24. LLNL Urban Eyes Through-Wall Detection System

The detector will monitor and display movement in the adjacent room. If movement is no longer detected and the person to be monitored is still present, the Urban Eyes can provide respiratory monitoring.

3. Results

The results of the experiment were collected both in the NOC and in Halligan Hall. The results were primarily screen shots at various portions of the experiment.

a. Collaborative Tool Results

The collaboration effort went well when connectivity provided by the MeshDynamics structured mesh was stable. Both video streams were visible and communications between all client nodes were maintained in a timely fashion. The video image triggered motion detection alerts in an expected manner when movement was detected by SA. The video image supplied by the UWB communications link could be viewed in SA with enough resolution to observe accurately the scenario. On the other hand, the video from Urban Eyes was very informative but the resolution of the video displayed in SA made portions of the screen difficult to ascertain some of the data presented. The breaths per second (BPS) functionality was difficult to read. The figure below illustrates the SA program with both video streams activated.

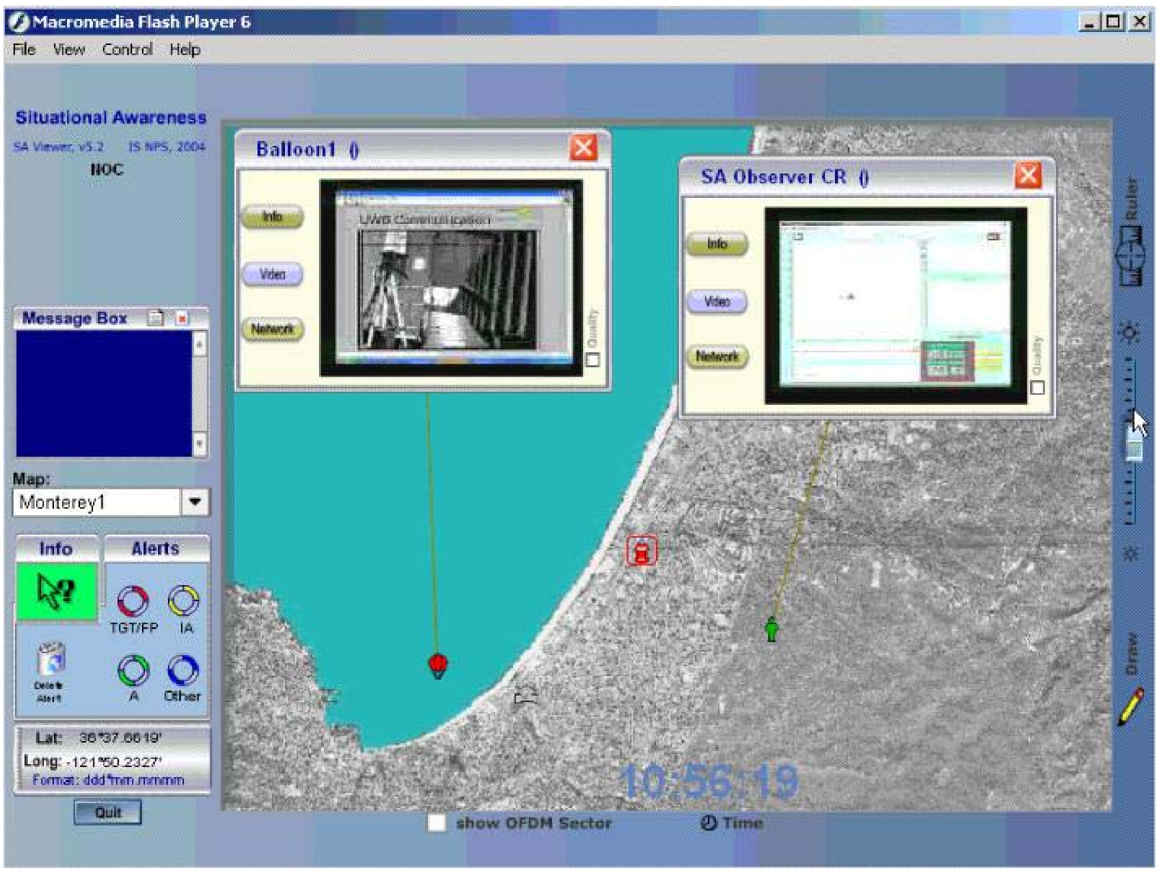

Figure 25. SA with UWB and Urban Eyes Video

The table below is a breakdown of the nodes represented in the SA program.

Node	Symbology	Geographic Location
NOC	Red Vehicle	NPS Gigalab
UWB Video	Red Balloon	NPS Halligan Hall Basement
Urban Eyes	Green Individual	NPS Halligan Hall Upstairs Classroom

Table 2. SA Node Representation for TNT 05-2

The video presented by the UWB data link through the multiple walls demonstrated the capability of UWB to supply a stable communications link. Despite the shortcomings of the structured mesh, the UWB through-wall communications link supplied video to the receiver effectively. Figure 21 illustrates the UWB supplied video prior to input into SA.

b. 802.11 Mesh Results

The MeshDynamics structured mesh had mixed results. The weather on the day of the experiment was not conducive to providing the ideal conditions for connectivity. I believe the continuous heavy showers played a significant role in the connectivity performance of the structured mesh. The mesh performed well when connectivity was established and maintained. I experienced frequent drops in connectivity and reduced throughput. I encountered throughputs of 120 kb/s to 2.5 Mb/s when connectivity was established. This throughput was measured over three hops. The illustration below depicts how the network was set up in the MeshDynamics Structured Mesh Network Management System.

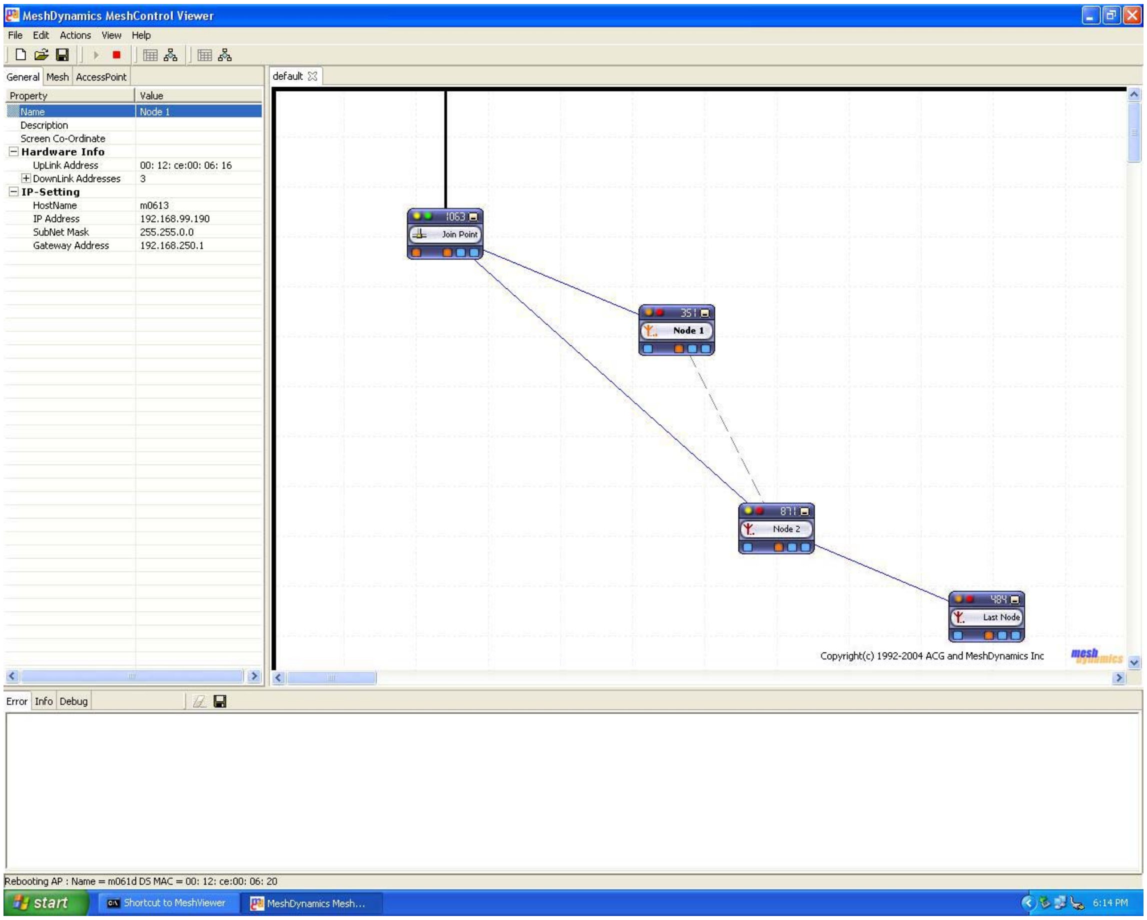

Figure 26. Mesh Dynamics Structured Mesh Network Management System

The spacing between nodes was approximately 200-300 feet. The Network Management System stated that according to the established set up the rated throughput per node was 18-25 Mb/s. I never experienced that rated throughput utilizing QCheck as the measurement device. I employed a client, accessing Node 2, and sent 100 kb TCP packets to the Solarwinds Server in the Gigalab. The highest rated throughput observed was 2.5 Mb/s. In a separate test, on a different day, with ideal weather conditions, and only two hops, I experienced 12 Mb/s.

c. *Ultra Wideband LPI/LPD Results*

The detection results were conducted by personnel from LLNL at the Livermore Laboratories located in Livermore, CA. The exact date of the results is unknown. The results in the figure below correspond with the transmitter used in the TNT 05-2 experiment at NPS.

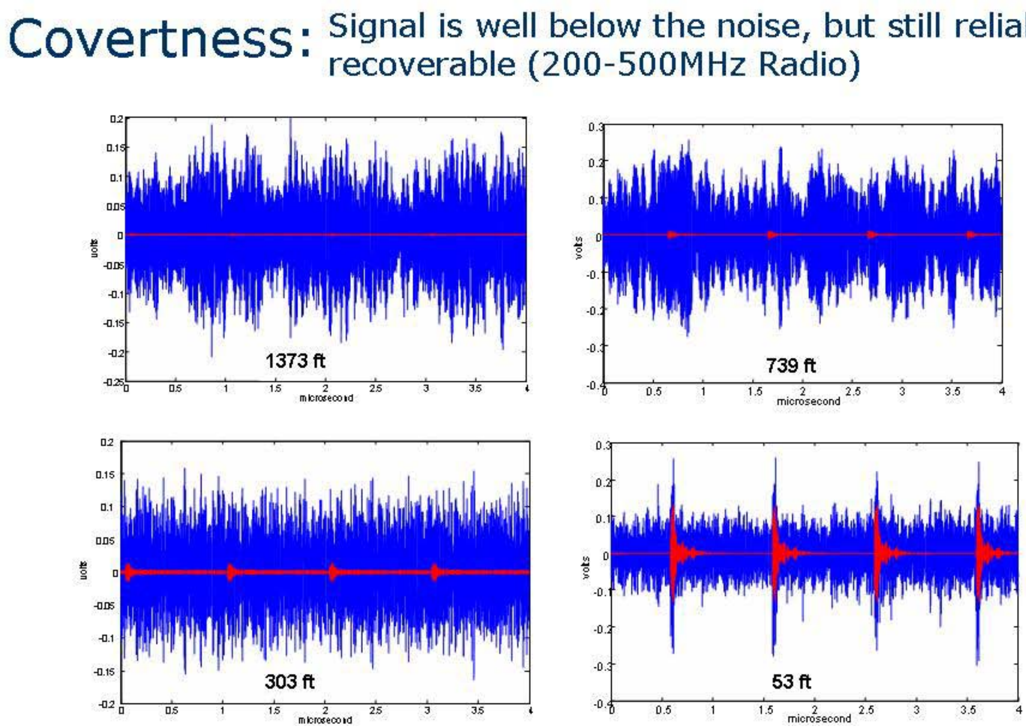

Figure 27. LLNL 400 MHz UWB Transmitter LPI/LPD Results (From Romero)[29]

The results show that at 1373, 739 and 303 feet the UWB signal is well below the noise threshold. At 53 feet is when the UWB pulses can be detected. In addition, I received the detection results for the transmitter used in the TNT 05-1 experiment. The figure below presents the results.

[29] Interview between C. Romero, Engineer, Lawrence Livermore National Laboratories, and the author, 4 March 2005.

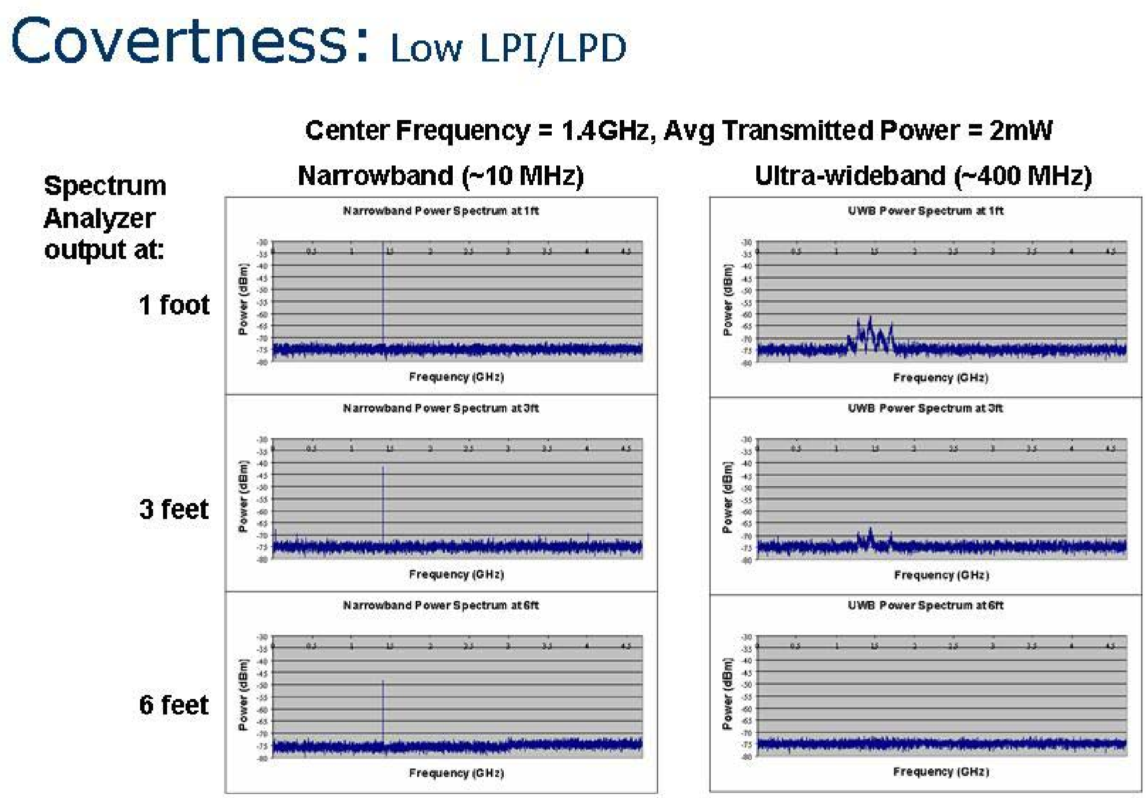

Figure 28. LLNL 1.4 GHz UWB Transmitter LPI/LPD Results (From Romero)[30]

The UWB transmitter above was being compared with a similar narrowband transmitter. As you can see, the results clearly display the covert capabilities of a UWB signal over a narrowband signal. At six feet, the UWB signal is lost in the noise and the narrowband signal is still very detectable.

d. Ultra-Wideband Radar Results

The Urban Eyes experiment was successful. The Urban Eyes effectively monitored the individual movement through the wall and provided a track history of the individual's movement. The figure below is an illustration of the interface between the operator and the transceiver set.

[30] Interview between C. Romero, Engineer, Lawrence Livermore National Laboratories, and the author, 4 March 2005.

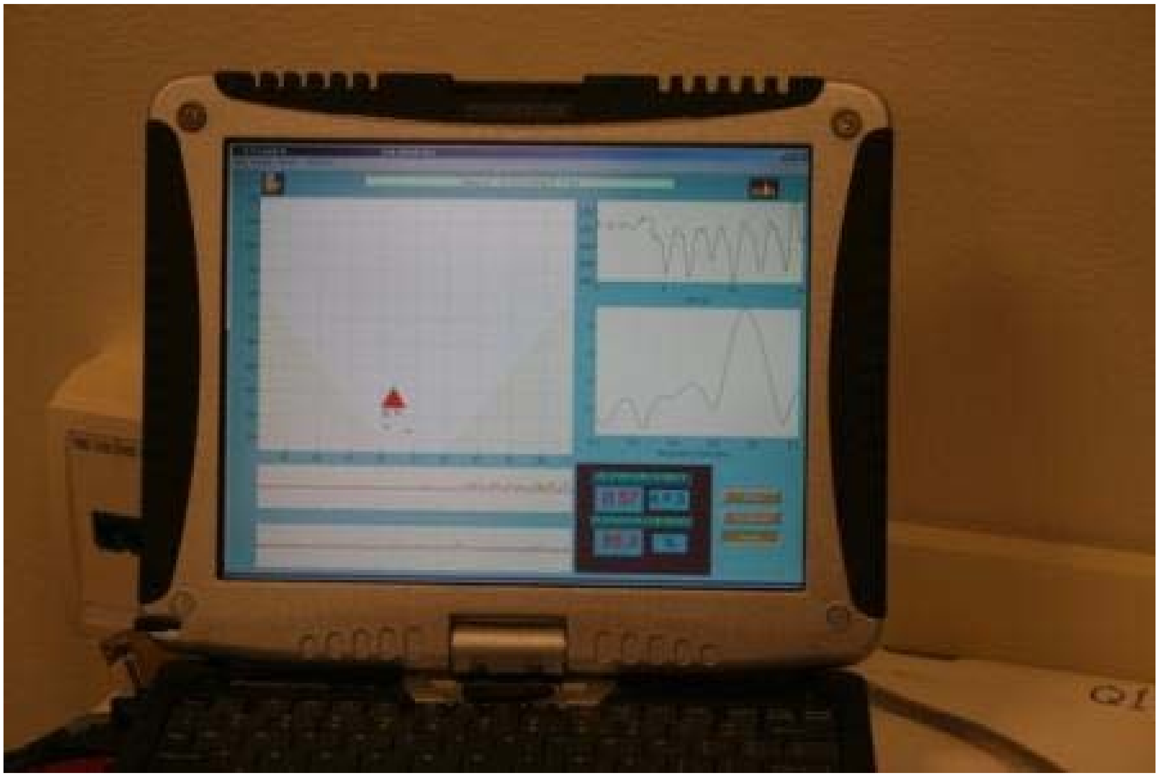

Figure 29. Urban Eyes Operator Display

The red diamond represents the target in motion. The black x's denote the track history of the target. Because the transceiver variant used in this experiment only had two units, only one target could be simultaneously tracked. The addition of a third antenna would enable the unit to track multiple targets through the wall. With this variant, if there is more than one target in motion, the target with the highest rate of motion will be tracked. If motion stops, Urban Eyes then focuses on the respiratory breathing attributes of the target. Urban Eyes will verify that the target is indeed a human and not a false alarm. The target breathing is measured in breathes/second and a confidence factor is assigned. This functionality provides false alarm detection in the event a dog or cat passes by or a fan is in motion for example. The device used in the experiment was connected via USB cables to the management software. A wireless version is also available providing up to a 500-meter stand-off capability. Urban Eyes provides a viable solution for room or building entry in an urban environment.

4. TNT 05-2 Conclusions

The collaboration effort using SA went well despite the connectivity issues with the NOC. The video that was provided would have given any operator a better sense of the situation ongoing. SA performed the duties as planned.

The verdict is still out on the MeshDynamics structured mesh. I believe the weather conditions hampered the connectivity between mesh modules. The rain also forced us to relocate the mesh modules in a less than ideal manner, which I also believe might have affected the connectivity. Future experiments and testing needs to be performed on the MeshDynamics mesh modules to truly ascertain their effectiveness to provide ubiquitous connectivity.

The performance data provided by LLNL clearly demonstrates the LPI/LPD advantages of UWB over other narrowband systems. A tradeoff exists between range and covertness. To have increased range you must transmit more power, which it turn, makes you more vulnerable to detection. Despite being detected, the interceptor will still have an extremely difficult time gathering the data off the signals because the coding and timing of the reference signals will be unknown to the interceptor.

The Urban Eyes demonstrated that UWB through-wall motion detection and tracking is an amazing product to be used in an urban environment. By knowing, what might lurk behind unknown barriers, clearly presents an added benefit to the soldier and the TOC. Decisions can be made with a higher degree of confidence then ever before. The situation awareness will be greatly improved and will ultimately save lives.

V. POSSIBLE APPLICATIONS

A. VISION OF UWB MESH

UWB technology appears to be the ideal physical layer alternative to current wireless communication links. UWB is still in its infancy but these early observations of UWB's abilities look very promising. UWB integration with mesh networking technology also holds a very high potential for success.

1. Shipboard Infrastructure

Onboard military vessels radio frequency spectrum allocation and electromagnetic interference issues are of great importance when considering new technologies to employ onboard. These issues make UWB a perfect fit for shipboard applications. UWB can be allocated across a large portion of the radio frequency spectrum and not interfere with any currently used equipment because to them UWB just appears as noise. In addition, the need for cables no longer applies, which consequently reduces electromagnetic interference. Currently onboard ships, problems exist with miles of dead ended cabling. I believe the incorporation of wireless networks would dramatically reduce the amount of necessary cabling. This would not only assist in the dead ended cable issue but also help reduce the added weight that cables place on a ships hull. A few possible shipboard applications are mentioned below.

a. Sensor Network

The amount of shipboard sensors is continuously rising with the concept of smartship. With the implementation of new systems and the modernization of existing systems, the amount of equipment requiring monitoring is increasing. Occasionally the amount of time and labor required to install these systems can be vast. A measure to reduce this time and labor allocation is to install these systems with wireless UWB mesh sensors. This enables each system to be online sooner with less shipboard intrusion. Another added benefit of a wireless UWB sensor mesh is the added security of redundant communication paths and low power consumption in the event of a shipboard casualty.

b. Shipboard Local Area Networks

The LAN onboard a ship is an integral part of the daily operations. The current configuration of the unclassified LAN is based upon Ethernet technology. The introduction of an UWB wireless LAN would provide a secure alternative to the conventional Ethernet based LAN. The inherent capabilities of UWB make it a viable solution. Some of the advantages gained by implementing a UWB LAN are:

- Provide high network availability for mobile laptop and PDA users
- Increased robustness in the event of a casualty
- Less required infrastructure
- No compartment intrusion entailed
- Ease of expandability

The use of a UWB wireless LAN will provide an easily configurable robust LAN solution for shipboard applications.

c. Perimeter Warnings and Ranging

UWB can offer a covert stationary radio frequency fencing around the ship. The UWB perimeter fencing can alert shipboard personnel of any breach in security while moored or at anchor. An adjustable range perimeter can provide varied levels of security depending on the threat condition and area of operations. The addition of a perimeter warning system will greatly enhance shipboard security and force protection.

UWB can also offer military vessels a short-range radar ranging system. This system would be ideal for maintaining station alongside during underway replenishments and mooring evolutions. With current radar systems, contacts become land locked or become lost in the radar clutter. UWB would supply a system without these problems and with a higher degree of accuracy.

B. GIG IMPLEMENTATION

The ability for the warfighter to access accurate real time information in a hostile environment is priceless. The goal is to increase the level of net-centricity available to the warfighter. The establishment of an UWB mesh network will be the enabler for successful Command, Control, Communications, and Intelligence (C3I) within the GIG at the tactical level. Every soldier and their equipment will become intermediate mesh nodes routing all timely and pertinent information to increase situational awareness in the battlefield. UWB technology will supply the physical layer solution providing the covertness and reliable network link the GIG needs for that last mile.

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VI. RECOMMENDATIONS AND CONCLUSION

A. CURRENT STATE OF TECHNOLOGY

The current work of LLNL and several other technology companies in the area of UWB show that promise exists in the world of UWB. Despite all the research efforts, UWB technology is still in its infancy in terms of its possible applications. The same efforts exist for mesh networking. Mesh networks offer an alternative solution to traditional infrastructure based wireless communications. The ability for each ad-hoc node to provide routing capability makes it an ideal networking model for military communications at the tactical level.

B. CONCLUSIONS

The mesh networking problems that were encountered during the experiments need to be resolved before any movement forward can be made in providing the last mile GIG solution in a tactical environment. I believe UWB has reached the point where it is ready for implementation into the mesh.

1. Feasibility, Functionality and Usability of UWB in Support of Military Operations

From my research and observations, current UWB technology offerings are ready to be implemented into the battlefield. With future funding and operational evaluations, I believe the UWB applications of through-wall detection and communications will impart a huge impact on the way military operations are conducted in an urban environment. The success demonstrated in the NPS TNT experiments provide proof that UWB technology is ready for the next level of development.

Current commercial products exist in the field of UWB, but I believe the alternatives that LLNL have developed provide a more definitive solution in the arena of military operations.

2. Feasibility of Implementing UWB as the Physical Layer Alternative in Mesh Networks in Support of Military Operations

As I previously mentioned, UWB is ready for the next step in development. On the other hand, I do not believe mesh network technology is ready for deployment at this time. More research and experiments need to be conducted to resolve the routing, connectivity, and throughput issues that were encountered during the past two TNT Field Experiments. UWB may be the answer for the connectivity problems that have been observed. Nevertheless, until definitive proof exists, the mesh architecture is the shortcoming in implementing UWB as the physical layer medium in a mesh network for the warfighter of the future.

C. POTENTIAL FUTURE RESEARCH

Future research in the areas of Mesh Networking and UWB need to focus on several key areas. They include: (a) mesh networking routing, connectivity, and throughput mechanisms; (b) investigate other vehicles of mesh integration i.e., Tactical Satellites (TACSAT) and the GIG; (c) refine the SA Program and attempt to collaborate with U.S. and coalition forces; and (d) develop more possible applications of UWB technology.

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